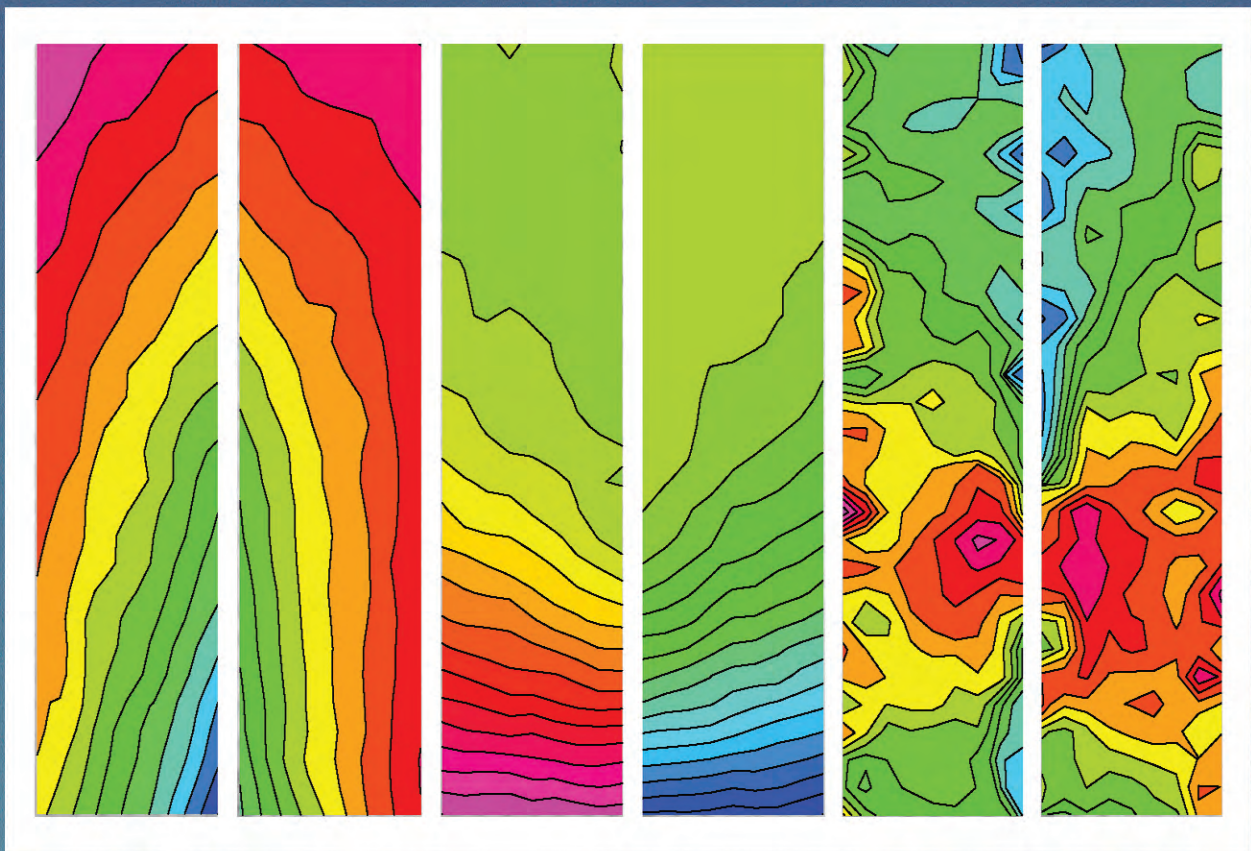


nuclear **weapons** journal



Spring 2004

- PBX 9501 Fracture ■ NWE Initiative ■
- Superhard Warheads ■ Polymer Characterization ■
- S5370 Replacement Testing ■ ICF Experiments ■



The World's Greatest Science Protecting America

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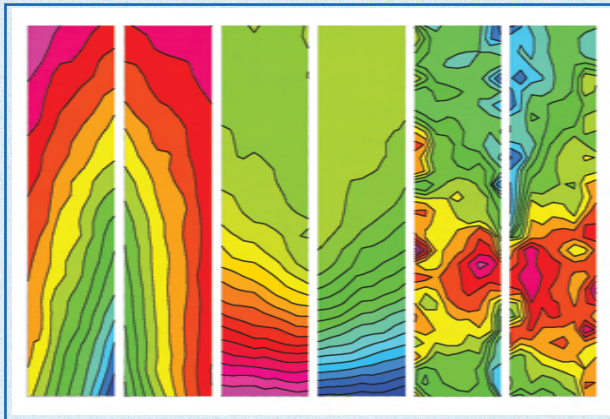
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About the cover: Contour plots of measured displacement and strain fields in a sample of PBX 9501 high explosive. The sample is a modified double-cantilever beam, where opposing loads are applied to cause the PBX 9501 to crack. The plots are shown at the moment when the applied loads reach peak value. Such studies of the failure resistance of high-explosive materials are essential to the Laboratory's stockpile stewardship mission because high explosives are critical components of the nuclear weapons in the stockpile.

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Point of View

**Alverton A. Elliott, Program Manager
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The Price-Anderson Amendments Act (PAAA), enacted by the US Congress in 1957 and renewed in 1988 and 2002, provides the legal framework for the regulation and enforcement of nuclear safety standards and establishes provisions for the indemnification and limitation of public liability arising from nuclear incidents.

In a sense, PAAA is an insurance policy that compels the Laboratory to comply with the nuclear safety requirements for protecting workers and the public. However, the Act also guarantees compensation to American citizens who incur certain injuries and costs as a result of a nuclear incident at a DOE facility.

The PAAA has four major elements. The Act

- covers all persons who are legally liable,
- protects DOE contractors from paying costs related to public liability arising from nuclear incidents,
- covers all DOE contractual activity that might result in a nuclear incident in the United States, and
- is mandatory for all DOE contractors, subcontractors, suppliers, and shippers.

The 1988 amendments extended the government insurance program, which was about to expire. These amendments differed from the original act in two principal ways.

- They made Price-Anderson coverage mandatory for all contractors, subcontractors, and suppliers who conduct nuclear activities

for DOE (for the purposes of the statute, “nuclear” includes “radiological”).

- They mandated that DOE change its methods of managing nuclear activities by requiring DOE to undertake enforcement actions against indemnified contractors for violations of nuclear safety requirements.

These amendments required that DOE establish a system of civil penalties for contractors who violate DOE nuclear safety regulations. This system was intended to improve accountability for nuclear safety during the conduct of DOE activities without affecting contractor indemnification. In 1996, DOE initiated a system of positive incentives to encourage the Laboratory to create a climate of nuclear safety through (1) a proactive system of self-identification of noncompliance issues and (2) reporting and correcting issues before they adversely impact individuals and/or the Laboratory.

Self-Identification

In 1995, the Laboratory established the PAAA Office to oversee LANL’s participation in the Act. By self-identifying noncompliances, we (1) demonstrate our commitment to an enhanced nuclear safety culture and (2) improve our performance by developing improvements to our processes.

The Laboratory’s nuclear weapons program is subject to the PAAA enforcement process, as clarified in DOE Enforcement Guidance Supplement 01-01, *Nuclear Weapon Program Enforcement Issues*, dated October 15, 2001. The Laboratory PAAA office works with the LANL weapons community and NNSA to finalize the list of nuclear weapons activities that are covered by PAAA enforcement and to ensure that the review process is in place

continued on page 31

Fracture Behavior of PBX 9501 High Explosive

An engineering or structural material is any material used to build or construct something. Such materials include wood, metal, concrete, polymers, diamond, and even DNA. Polymers alone comprise an enormous number and variety of these materials. We are studying stress, strain, and fracture in high explosives (HE) as engineering or structural materials.

Determining the failure resistance of high-explosive materials is essential to stockpile stewardship.

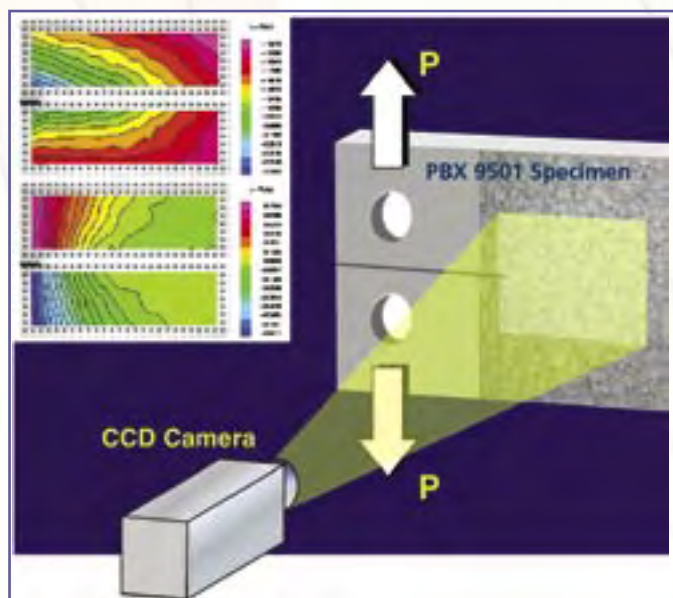
Almost all engineering materials contain defects, very often in the form of cracks. Under externally imposed loading, either mechanical or thermal, these preexisting defects may grow and new defects may form, resulting in fracture. The simplest definition of fracture might be both “the process of breaking” and “the condition of being broken.” These two choices are inseparable, in that only after we better understand the process of breaking can we better predict the conditions under which the material will be broken.

High explosives are critical components of the nuclear weapons in the stockpile. The application of fracture mechanics analysis to determine the failure resistance of high-explosive materials is essential to the Laboratory’s stockpile stewardship mission.

High-melting explosive is called HMX. The plastic-bonded HMX high explosives, called PBX, are composed of energetic crystals (HMX) and a polymeric binder. Internal cracking in HE is believed to be a dominating mechanism that affects the mechanical performance of HE and may even trigger detonation under suitable loading and environmental conditions.

Previous experiments have shown that the fracture process in PBX 9501 is very different from that in brittle solids, even though PBX 9501 is quite brittle under tensile load. Close examination of fracture surfaces revealed that before crack initiation and propagation occur, a large damage region develops at a location in front of the crack tip. Because such damage regions are very narrow, they can be modeled as cohesive zones.

Because sizable cohesive zones are present, conventional fracture mechanics is no longer applicable. The fracture behavior of PBX 9501 cannot be characterized by just one critical parameter, for



Schematic of the modified compact double-cantilever beam specimen and optical setup for studies of crack propagation in PBX 9501. A pair of forces (P) applied to the sample in opposing directions cause it to begin to separate. A pre-notch with known geometry is machined into the specimen. Under the applied load, a cohesive zone forms at the tip of the pre-notch, and crack propagation follows. A speckle pattern painted on the surface of the sample around the notch tip enhances optical data collection. A CCD camera records images of the pattern during the fracture process. We then use the DIC technique to process digital images to obtain the displacement field surrounding the pre-notch tip at different times.

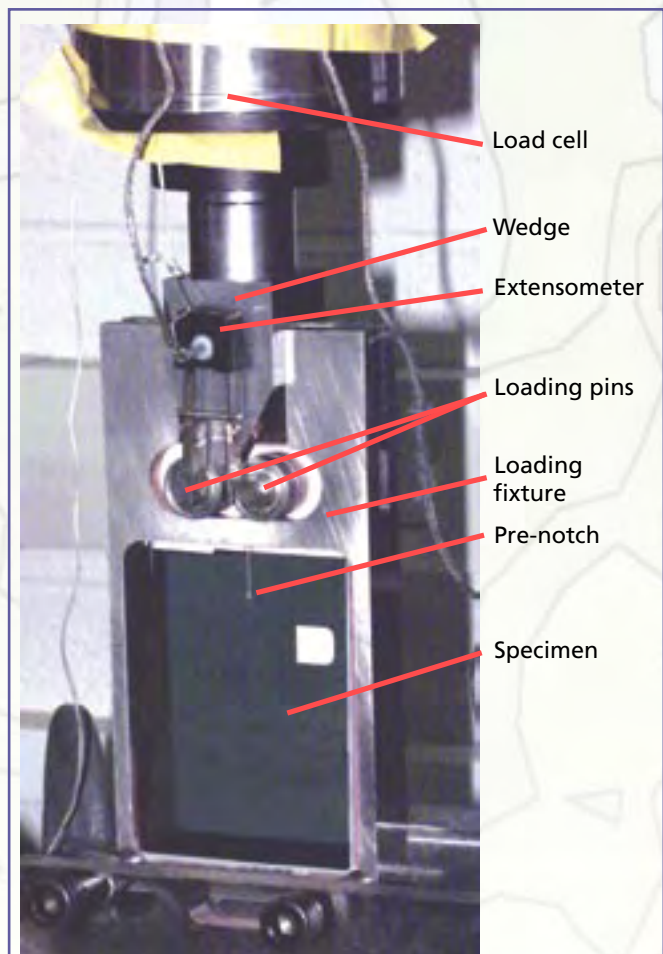
example fracture toughness, as in the classical fracture mechanics approach. Instead, the entire process of cohesive-zone initiation and extension, as well as subsequent crack propagation, must be described explicitly. Material decohesion must be considered and quantified if we are to understand and model the fracture processes in PBX 9501.

During the past several years, we applied the digital image correlation (DIC) technique to study deformation, damage evolution, and fracture processes in HE and mock materials. The DIC technique relies on the computer vision approach to extract whole-field displacement data, that is, by comparing the feature in a pair of digital images of a specimen surface before and after deformation. The specimen we used to study the fracture process in PBX 9501 in a modified double-cantilever-beam (DCB) has a “pre-notch” of known geometry. We painted a random speckle pattern on the surface of the sample to provide the optical feature needed in the DIC processing, and we used a charge-coupled device (CCD) camera to record images of the speckle pattern as the PBX 9501 specimen fractured.

During the test, series of digital images were recorded at different times. Using the DIC technique, we converted sequences of images to the whole field of deformation gradients and then to strain components.

Using the strain field obtained through the image correlation calculation, we can determine the stress field at each moment. As a result, the cohesive stress can be obtained from the stress component normal to the notch and along lines just above and below the fracture plane. Meanwhile, the opening displacement across the fracture plane can be obtained from the displacement field. Finally, we graphed the variation of the cohesive stress as a function of the opening displacement across the fracture plane for arbitrarily chosen moments to represent the decohesion law for PBX 9501.

The plot of the PBX 9501 decohesion law shows that cohesive stress rises very steeply and peaks at a small opening displacement. This behavior is consistent with that of PBX 9501 in uniaxial tension. In tension, PBX 9501 fails at about 0.1% to



Double-cantilever beam loading fixture and specimen setup. The specimen with a pre-notch is firmly attached at the bottom of the loading fixture. A wedge moves downward, pushing the two loading pins apart, applying opposing forces to the specimen and forcing it to crack. The load cell and the extensometer, respectively, monitor the applied load and the separating distance between the two loading pins during the test. A CCD camera (out of view in front of the setup) records images of crack propagation during the test.

0.15% of tensile strain, which is very small compared to failure in compression. After the peak cohesive stress, the decohesion law has a very long tail, a fact that explains why the classical fracture mechanics approach ceases to work for PBX 9501.

The decohesion law obtained from the fracture experiments demonstrates that PBX 9501 fracture follows the sequence of elastic loading, cohesive-zone enlargement, and crack extension. Moreover, the initiation of the cohesive zone occurs before the applied load reaches its maximum value, a condition that suggests that damage formation and evolution

are dominating factors during the entire deformation process in PBX 9501.

The decohesion law, which governs how fracture occurs in the material, is a material property similar to elastic constants and other material parameters. We believe that the decohesion law will also depend on loading rate, temperature, and other ambient conditions. We are currently pursuing studies of the effects of these conditions on the fracture behavior of PBX 9501.

In our experiments, we treat PBX 9501 as a homogeneous medium to determine the decohesion law; however, the heterogeneous microstructure of the material still plays an important role in the apparent decohesion behavior. Investigations into the following areas of micromechanical influences would contribute to our understanding of the decohesion behavior:

- the influence of the constitutive behavior of the

HMX crystal, the polymeric binder, and the interface between the two on the breaking behavior of the composite; and

- the role of the distributions of different HE microstructures in the fracture resistance properties of the materials.

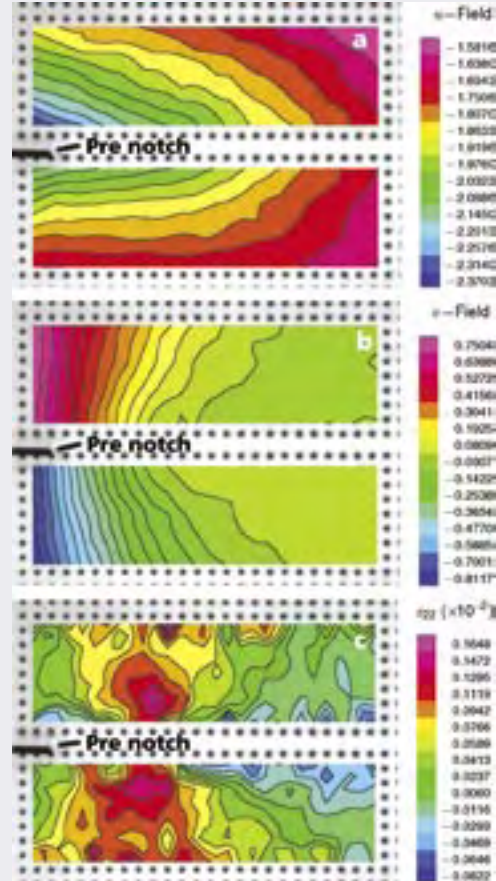
The measured decohesion law can be implemented into a finite-element computer code to simulate the fragmentation process in HE during impact. Researchers in ESA-WR simulated the impact of a cylindrical sample of PBX 9501 on a rigid plate at 30 meters per second (m/s), in an experiment called the Taylor cylinder impact test. To capture the fragmentation of high-explosive material, an interfacial element with zero-thickness is implemented between any two adjacent structural finite elements. The structural element is used to characterize the “bulk” behavior of PBX 9501, while the interfacial element is used to capture the breakage of the material. The deformation of the interfacial element is

Contour plots of measured displacement and strain fields at the moment when an applied load reaches its peak value: (a) horizontal displacement field, (b) vertical displacement field, and (c) field of normal strain perpendicular to the fracture plane.

Displacement vector characterizes the motion of a material particle in a plane. The vector has two components: the u-component along the horizontal direction and the v-component along the vertical direction. Color bars for the two displacement contour plots (a) and (b) indicate the magnitude of the displacement measured in pixels (here, 1 pixel = 0.053 mm).

Strain, a tensor, characterizes how a material element stretches or deforms under applied load. Strain can be related to the gradient of the displacement field. Figure (c) shows only the normal strain component that measures the stretching of a material element in the direction perpendicular to the crack. The color bar for (c) indicates the magnitude of the strain in percentages.

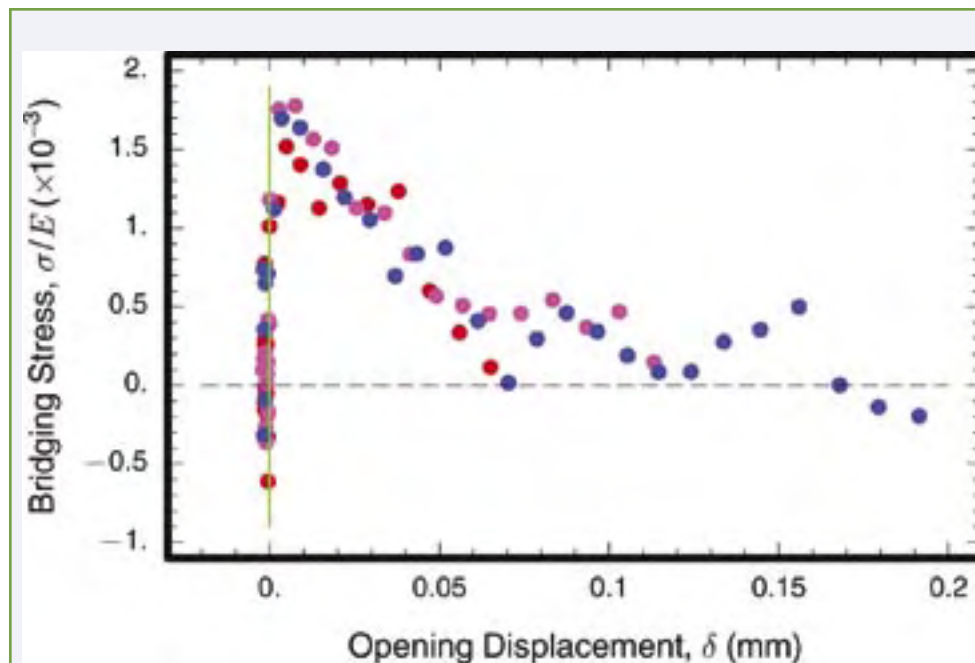
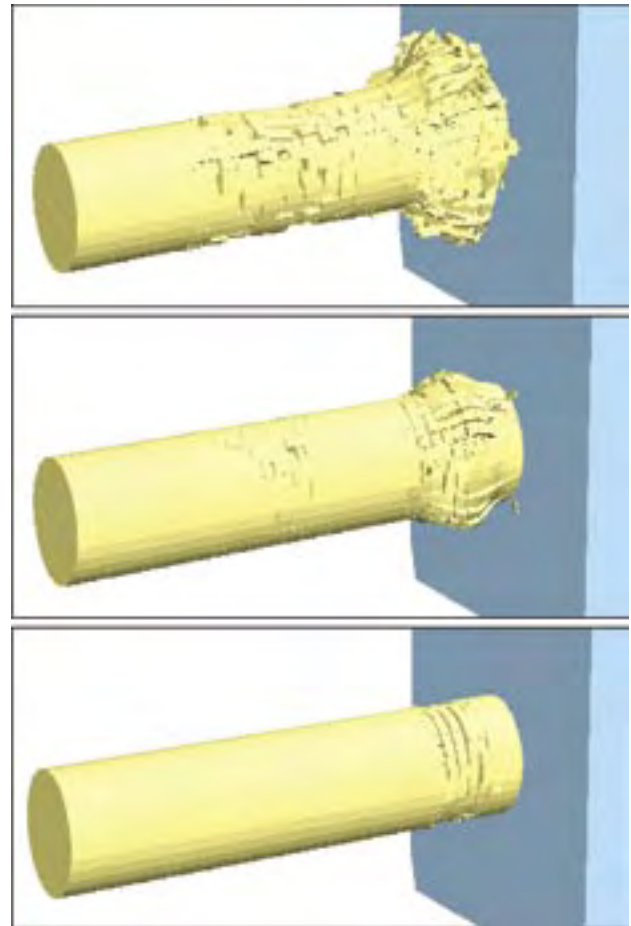
No visible crack extension (or material separation) shows in the images prior to this moment. However, the image in (c) shows that the high-strain region is not around the pre-notch tip. Instead, it appears at a finite distance in front of the pre-notch tip, indicating that a cohesive zone has developed at a location in front of the pre-notch tip.



characterized by an appropriate decohesion law. The preliminary simulations indicate that the fragmentation behavior of the HE material is very sensitive to the details of the decohesion law: changing just one characterizing parameter of the decohesion law caused completely different fragmentation behavior. Currently, researchers in both MST-8 and ESA-WR are working on developing material models and finite element simulation schemes that will capture the accurate details of fragmentation and fracture of PBX 9501 high explosive. [NWJ](#)

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The measured decohesion law can be implemented into a finite-element code to simulate the fragmentation process in HE during impact, as in this numerical simulation of the Taylor cylinder impact test. A cylindrical sample of PBX 9501 is launched at the speed of 30 m/s and impacts a rigid plate. The simulations show the same impact test at the same moment (0.625 ms after impact), while changing a parameter that characterizes the decohesion law. Completely different fragmentation patterns, reading from the top down, range from disperse fragmentation with secondary region of large fragments to less pronounced fragmentation with secondary fracture to localized planar fracture. These simulations indicate that the fragmentation behavior of the HE material is very sensitive to the details of the decohesion law.



Graph of the decohesion law of the PBX 9501 high explosive under quasi-static loading conditions. The heterogeneous microstructure of the material plays an important role in the apparent bridging behavior. The critical opening displacement at which the cohesive stress drops to zero and new material surface will be generated is on the order of 100 μm , which is about the average diameter of the HMX crystals.

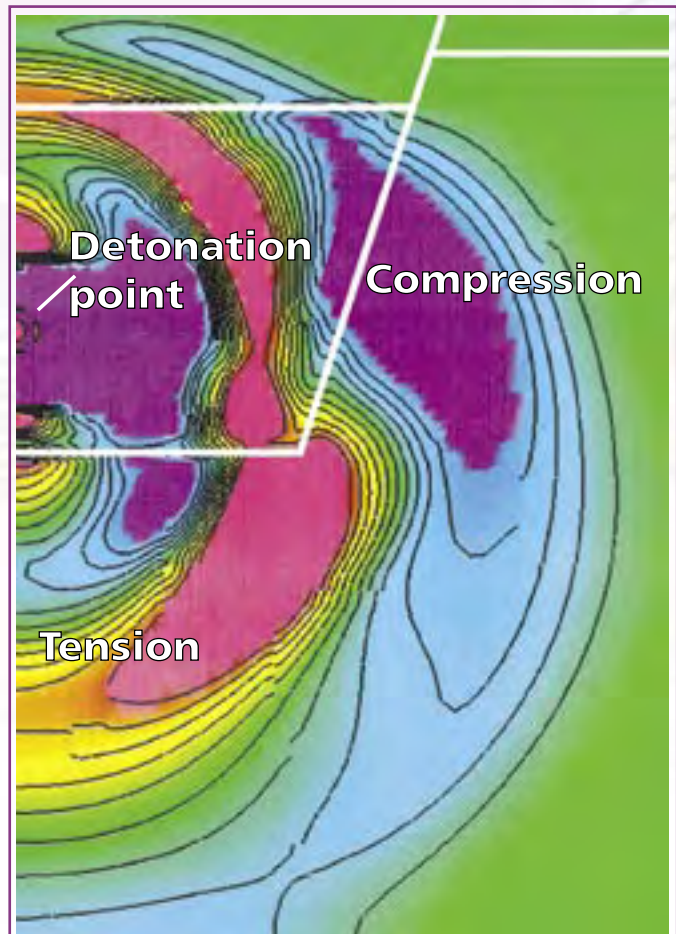
Nuclear Weapon Output and Effectiveness Initiative

Our changing national security environment has complicated nuclear deterrence strategies so that they potentially include scenarios with limited use of nuclear weapons that have specific effects and that result in minimal collateral damage. This approach is known as “effects-driven design.”

Simultaneously, the rise of rogue nations and sophisticated terrorist organizations has caused the United States to assess, and attempt to respond to and mitigate, the effects of potential nuclear devices that might be directed toward this nation. Nuclear deterrence and homeland security demand high levels of nuclear weapon effects (NWE) expertise and predictive capability. Los Alamos has played a central role in revitalization planning at the national level to rebuild a strong NWE program.

Historically, much of our nation’s NWE expertise centered in the DoD. Within that organization, the Defense Threat Reduction Agency (DTRA) and its predecessors, such as the Defense Nuclear Agency, were responsible for NWE research and development of predictive tools, while Strategic Command (STRATCOM) used those tools in military planning. DOE/NNSA and three of their national laboratories also had key roles in the following areas:

- weapon design and development, and output analysis and qualification testing;
- development of high-fidelity computational codes and high-performance computing platforms used by the NWE community;
- application of existing expertise to specific NWE issues such as defeat of hard and deeply buried targets, defeat of chemical and biological agents, electromagnetic pulse (EMP), and fireball dynamics;
- assessment of the survivability of nuclear and nonnuclear components in hostile and fratricide radiation environments and development of methods to mitigate those effects; and
- maintaining under- and above-ground experimental test facilities for certification and validation of codes and designs.



Cross section of a three-dimensional simulation of shock propagation a short time after detonation of an underground nuclear explosion, using an ASCII code. Colors and contours indicate pressure. White lines indicate locations of geologic discontinuities that produce changes in material properties.

Reversing the Trend

During the 1990s, capabilities for predicting NWE deteriorated within the DoD and DOE/NNSA communities, but efforts to reverse this trend are under way. In early 2002, LANL, SNL, and LLNL worked with NNSA to assess the state of the national NWE enterprise and NNSA's future role in it. This assessment, coordinated through NNSA's Nuclear Survivability Campaign (Campaign 7), determined not only the need for a program to rejuvenate and steward NWE capabilities, but also that the three NNSA laboratories, in coordination with DTRA and STRATCOM, have important roles in this mission. These roles are further strengthened by the emerging needs of homeland security and nuclear deterrence.

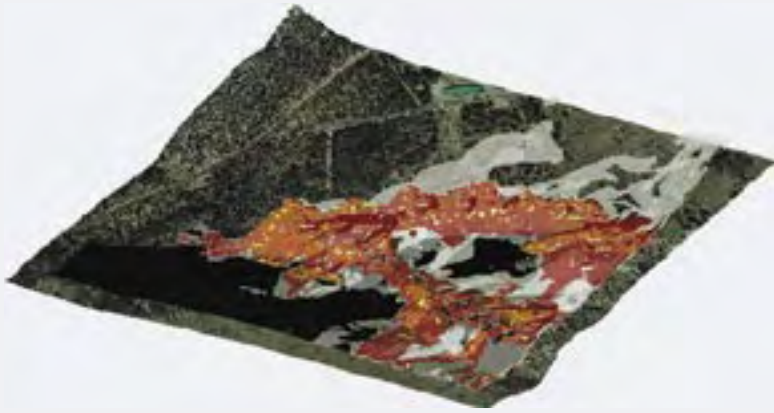
Los Alamos is key to revitalizing a strong NWE program.

In fall 2002, NNSA sponsored a series of workshops that involved about 100 scientists from NNSA laboratories. The workshops assessed the needs of the NWE community (STRATCOM, Homeland Security, US Air Force, US Navy), set research priorities and goals, and drafted a potential 5-year program. By summer 2003, a full program plan was incorporated into Campaign 7, as a major technical effort. Campaign 7's main efforts—weapon output, survivability of nuclear and nonnuclear components, and NWE—were developed within this expanded scope.

Campaign 7 was renamed the Nuclear Survivability and Effectiveness Campaign, focusing on the following areas.

- *Weapon output.* To ensure the survivability and effective design of our nuclear weapons, NNSA must be able to compute all aspects of weapon output, including the output of adversary warheads. Output assessment encompasses knowledge of radiation transport in complex, geometrically divergent hydrodynamic flows in physical regimes not normally encountered elsewhere. To ensure output credibility and quality, the design laboratories defined and commenced a
- *Survivability of nuclear and nonnuclear weapons components.* The increased emphasis on stockpile life-extension calls for reevaluating the role of nuclear survivability assessment within the stockpile surveillance program. In addition to initial survivability qualification, we must develop new strategies to monitor and maintain nuclear survivability over the lifetimes of our nuclear weapon systems. These strategies must be consistent with the constraints of the stockpile surveillance program, must ensure that stringent nuclear survivability requirements are met, and must rely on technologies that will be available to NNSA in the future through its laboratories or through industrial and/or other governmental sources.
- *Nuclear weapon effects.* This major new technical effort includes the following issues that are vital to predicting nuclear warhead effectiveness and its relation to weapon design:
 - hard and deeply buried target defeat—prediction of weapon energy coupling into ground for various devices and penetration depths, propagation of ground shock through complex and heterogeneous geologic media, and response of underground facilities to shock loading;
 - agent defeat—prediction of thermal and radiation environments in a chemical- or biological-agent storage facility, container and agent response to that environment, turbulent agent sweep-up and mixing within a rising fireball, and the effects of all these actions on the agent itself;
 - EMP and high-altitude effects—development of high-fidelity capability to predict (1) weapon design influence on EMP environments over the full range of EMP time scales at all altitudes and (2) other high-altitude effects such as the interaction between weapon output and debris and the earth's radiation belts;

formal competitive and collaborative peer review process that ranges from detailed comparison of calculational results to more traditional review of each others' work.



LANL fire simulation code FIRETEC predicts the spread of fire over complex terrain. The code fully couples to weather data in the area of impact. This code is being adapted to predict the spread of urban-area fires caused by the detonation of a nuclear weapon.

- nonideal air blast—prediction of asymmetric coupling of weapon output into air and propagation of shocks in complex settings (caused by topography or urbanization), particularly for low-yield devices and nonideal height-of-burst;
- fallout—transport of bomb and activated target debris to low and high altitudes and the subsequent fallout, focusing on heavily debris-laden plumes, chemical/biological agent-containing plumes, and complex terrain and weather; and
- fire—prediction of fire ignition and spread from nuclear detonations, particularly in urban settings, and the resultant collateral damage.

Coordinating with Other NWE Groups

A key aspect of NNSA's developing nuclear weapon design and effects program is coordination with other organizations that have NWE interests or missions. This symbiotic relationship evolved in many areas, spearheaded at NNSA by the Nuclear Survivability and Effectiveness Steering Group (NSESG). NSESG advises the assistant deputy administrator for research, development, and simulation at NNSA Headquarters and incorporates input from NNSA laboratories, DTRA, STRATCOM, the US Air Force, and US Navy.

Another important coordinating body is the Nuclear Weapons Effects Users Group, which was initiated by STRATCOM, DTRA, and the United Kingdom's Atomic Weapons Establishment to prioritize, plan, and conduct technical reviews of

NWE work in the weapons community. Over the past 2 years, the users group has expanded greatly and NNSA joined as co-chair. Five subgroups, each of which focuses on a specific technical area, provide detailed input to the users group; Los Alamos is represented in each subgroup.

In an advanced-concepts technology demonstration project, STRATCOM, the three NNSA laboratories, and DTRA are collaborating on defeat of hard and deeply buried targets. NNSA and DTRA coordinate the NWE programs they propose; joint working groups coordinate collaborations with the United Kingdom. Los Alamos coordinates with the Center for Homeland Security on issues related to potential nuclear terrorism within US borders.

Ensuring Nuclear Survivability

The Laboratory's long-term NWE program will ensure the survivability of US nuclear weapons, principally the nuclear assemblies carried aboard submarine- and silo-based strategic missiles. The environments produced by potential nuclear-armed ballistic missile interceptors include nuclear radiation such as neutrons, x-ray and gamma photons, and blast. These environments can produce fissile-material heating, damage to critical components, thermostructural response, external and internal EMP, and acceleration loads.

The program's success requires an understanding of (1) the operation and output of nuclear weapons; (2) radiation transport; (3) interactions with individual weapon components and major assemblies;

and (4) the sensitivity of weapon performance to material properties, particularly as the weapons age.

Extending the planned service life of the nuclear weapons stockpile from 15 or 20 years to many decades—while complying with current restrictions on underground nuclear testing—has altered certification and verification procedures. The vulnerability and hardening program now involves a more extensive and interactive combination of analysis and simulation experiments, a database of past experiments, and computer programs. Close cooperation with other organizations—including production plants, aeroshell and reentry systems

designers, weapons systems electronics designers, and the military services—is critical.

In summary, NWE is vital to the Laboratory's role in addressing evolving national security issues. Through active planning and coordination with other agencies, LANL promotes and maintains a central role in sustaining long-term stewardship of NWE capabilities. [NWE](#)

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Key Terms

agent defeat—destruction of a chemical or biological agent's ability to be used as a weapon

certification—confirmation that the Los Alamos nuclear weapons stockpile is safe and reliable

Each year, the nuclear weapon laboratories report the results of their assessments of warhead safety, reliability, and performance. DOE and DoD then transmit these results to the President of the United States.

chemical or biological agent—material that can be "weaponized," with the goal of causing major health effects for a specific population

coupling into ground—transfer of energy from a nuclear detonation into the surrounding medium

fratricide—unintentional malfunction in an offensive nuclear weapon (thereby preventing its full, intended performance) due to the nearby detonation of another offensive weapon

hard and deeply buried target—military facilities (e.g., command and control, weapons storage) installed at depths intended to evade the effects of conventional and/or nuclear attack from the surface; also may be designed to absorb and mitigate shock waves and their effects

hostile environment—region surrounding a nuclear detonation of an enemy ballistic missile defense asset; characterized by elevated radiation, strong electromagnetic pulse, shock and blast effects, and large quantities of explosion-generated debris

nuclear weapon output—energy in x-rays, gamma radiation, neutrons, and large quantities of explosion-generated warhead debris produced by a nuclear weapon as a function of time and space

shock loading—forces on and deformation of a target that are produced by the passage of stress waves

survivability—ability of a nuclear weapon to perform as designed during and after exposure to a hostile environment

validation—demonstration that a predictive model duplicates experimental data that capture all or some of the important physics in a model

vulnerability and hardening program—effort to understand the mechanisms and mitigate the effects that limit the survivability of a nuclear weapon system

Why Robust Deep-Earth-Penetrating Weapons?

Hypersonic (\geq Mach 5), precision-guided, long-range, and redirectable cruise missiles are the ultimate weapons in time-critical and high-value strategic strike applications. However, increased penetrating power—that occurs at hypersonic velocities—has prompted intensive research at Los Alamos on materials used in the hard “noses” of deeply penetrating weapons.

Currently, the hard noses of most penetrating bombs in the US arsenal are made of hardened alloy steels, high-density tungsten (W) alloys, and/or depleted uranium (DU) rods embedded in a steel shell. Metal alloys deform plastically under high-speed impact, where extreme pressure and temperature exceed the materials' yield strength. Although W and DU are much harder and denser than steel alloys and can concentrate greater

power at the point of penetration, the hard noses of W-DU penetrators also deform and blunt quickly on impact at very high speed. This blunting and deformation significantly reduce penetrating power.

At Los Alamos, we are researching superhard penetrator core materials for use in the nose cones of hypersonic, deep-earth-penetrating weapons. These materials are superhard and ultratough nanocomposites of diamond/cubic boron-nitride and/or diamond/silicon-carbon. Superhard warhead nose cones made of consecutive superhard rods with deep-piercing, self-sharpening, and blast-cleaning features are highly promising for hypersonic high-speed penetration.

Hardness is strongly correlated to ballistic

performance in penetrator materials. High-hardness materials perform well as ballistic projectiles but are more susceptible to brittle fracture and blast shattering. The intrinsically strong covalent bonds of these superhard materials form very tight crystal structures that ensure successful dynamic impact and deep-penetration warheads. Lightweight, superhard, and ultratough, these nanocomposites leave room in the missile for propellant fuels and high explosives and offer superb penetrating capability.

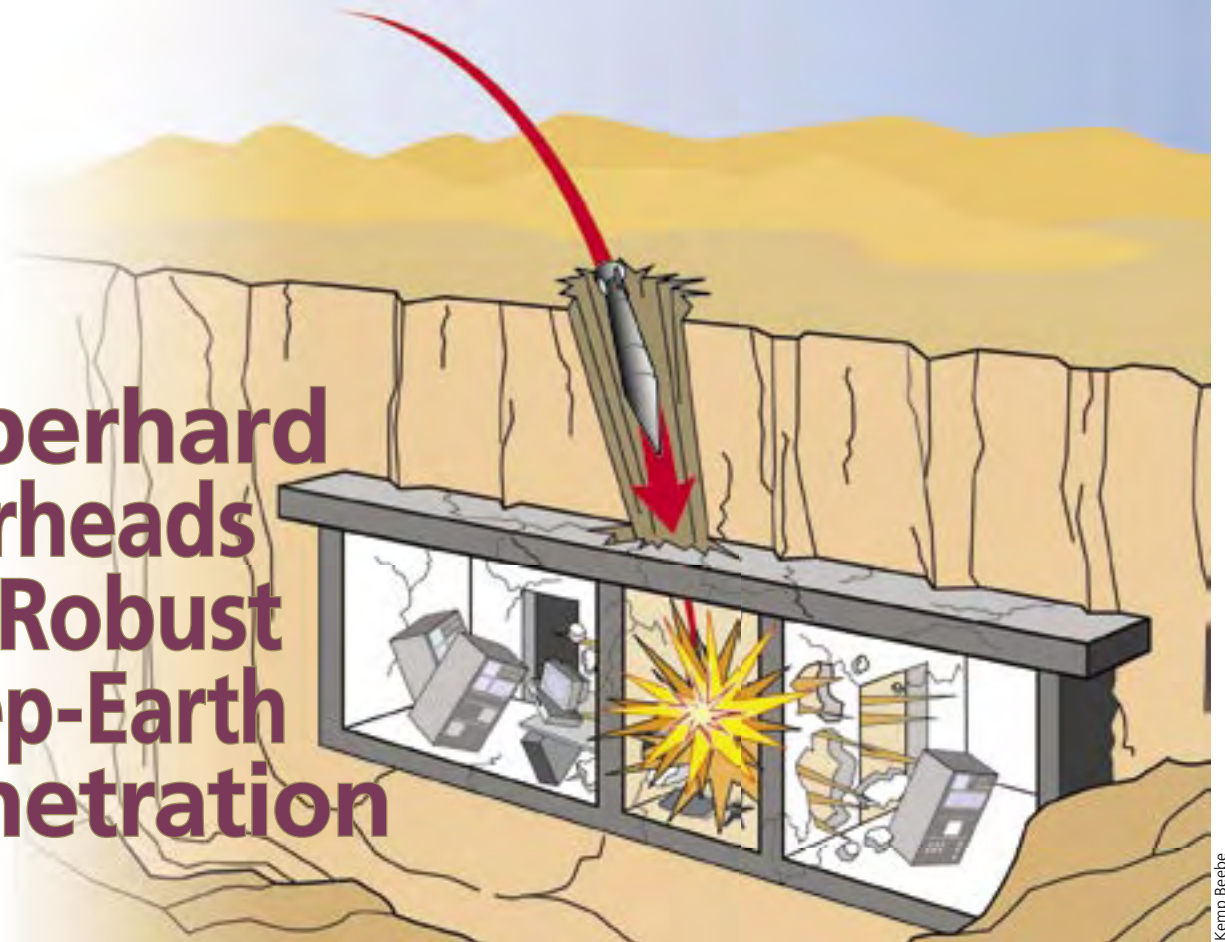
Superhard materials in warhead penetrators will significantly enhance the technological advantages of US weaponry.

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A swift global striking weapon system greatly decreases flight-to-target time, giving the system's command, control, communications, and intelligence functions more time to identify time-critical threats. Prompt and decisive, powerful earth-penetrating warheads blast deeply buried/hardened enemy targets, such as strategic command/control bunkers and/or storage tunnels of nuclear/chemical/biological weapons.



Superhard Warheads for Robust Deep-Earth Penetration



Kemp Beebe

Until recently, research on the penetrating power of impacting warheads focused on kinetic energy, which transforms to crater energies through impact, vaporization, melting, fracturing, and blasting at extreme pressure (P) and temperature (T). However, research in atomistic-level structural controls in nanocrystalline materials—materials the size of 1 nanometer (nm), or one-billionth of a meter—could revolutionize traditional material designs for many weapons applications.

The increase in the ratio of surface to core volume and the significantly altered strain energy of a composite solid in its nanocrystalline phase often produce qualitatively new physical and/or chemical behaviors. Deformation and yield occur when vacancies and dislocations in crystalline materials multiply and propagate.

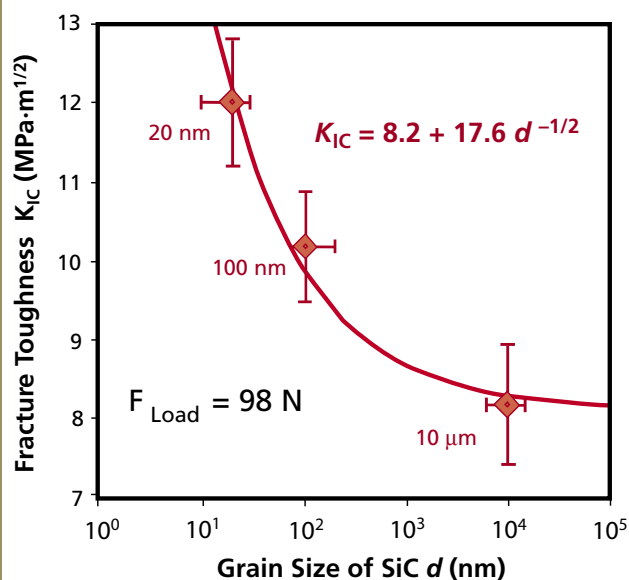
Initiation and growth of microcracks in the grain boundaries of ceramics and metal alloys lead to much lower practical hardness, toughness, and strength than theoretical values indicate. Those defects are greatly minimized in a material's nano-

crystalline phase; such minimization substantially enhances mechanical performance. Research shows that hardness and strength can increase by a factor of 3 to 5, and the bulk modulus (the measure of volume change with pressure) can increase as much as 30% to 50% when the grain size of a crystalline phase is decreased to the nanometer range. Such strengthening is caused by the decreasing number of vacancies and dislocations in the crystal lattice and the significant enhancement in surface energy as crystalline grain size diminishes.

Lightweight, superhard, ultra-tough nanocomposites have great potential in weapons applications.

Advantages of Superhard Nanocomposites

In a nanocomposite, a microcrack is comparable in size to a nanocrystal. To grow further, the crack would consume much more energy as it grows around the nanocrystals. This characteristic would decrease crack propagation ability, thus enhancing the material's fracture toughness. The results of



Nanostructured diamond/SiC composites, showing the relationship between the fracture toughness of the diamond/SiC composite and the grain size of its SiC matrix. Diamond-shaped symbols indicate measured fracture toughness values for the corresponding SiC grain sizes.

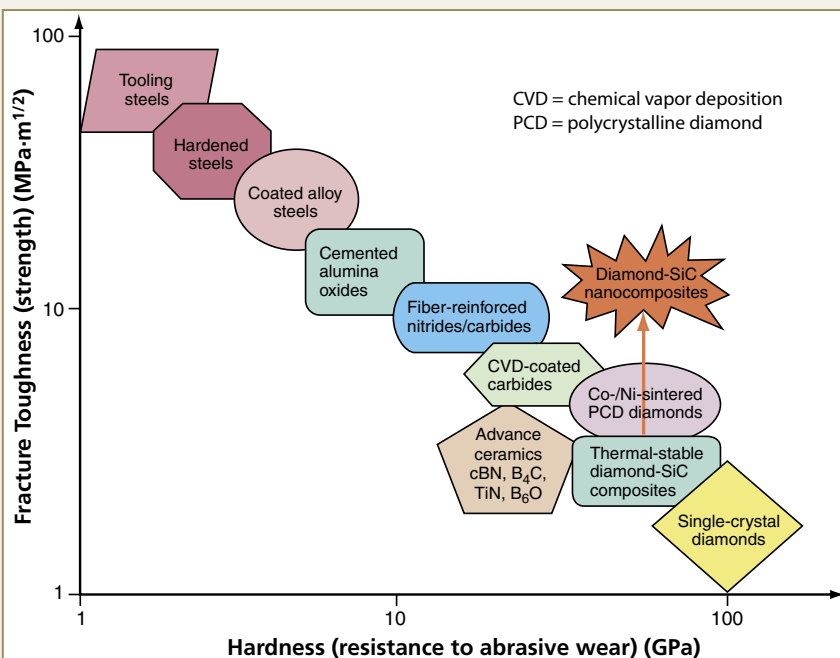
All measurements are conducted at a constant loading force of 98 Newtons. The equation $K_{IC} = 8.2 + 17.6 d^{-1/2}$ expresses the curve. The curve represents a fit to the Hall-Petch relationship (i.e., material hardness and yield stress typically increase with decreasing grain size).

our work to enhance the fracture toughness (K_{IC}) of a diamond/silicon-carbon (SiC) composite by as much as 50% (K_{IC} from 8 to 12 MPa·m^{1/2}) is a significant achievement in nanosynthesis and nanomechanics.

However, we still have little information about the demonstrated phenomena or practical implications of nanoscale phenomena. Furthermore, differences between micro- and nanocomposites pose real

technological challenges for production. Fast grain growth, which leads to irreversible loss of the unique properties of nanosize crystals, often occurs during the sintering process as a result of enhanced diffusion at surfaces and/or grain bulk.

One major task in our nanosynthesis study was to develop a practical way to control grain growth while introducing carbon nanotubes in the high P-T reactive sintering process. Also, the extraordinarily



Fracture toughness compared with materials hardness. Our results shatter the common acceptance of an inverse relationship between hardness and fracture toughness for most materials.

Our study provides a practical way to overcome this limitation and simultaneously achieves superhardness and high fracture toughness. To the best of our knowledge, this is the first experimental demonstration of the effect of nanoscale on fracture toughness of bulk composite material.

high tensile strength and high elastic modulus of the nanotubes may provide the means of fabricating nanotube-reinforced composite materials, much like steel-bar reinforcement in concrete. This advanced technology has great potential for producing extremely strong and ultralightweight materials.

Fundamental properties such as yield strength (σ_y), indentation hardness (H_v), elastic modulus (E_y), fracture toughness (K_c), and melting temperature (T_m) are major considerations for superhard materials used for deep-penetrating purposes.

For example, the material properties of depleted uranium (DU) and hardened alloy steels (e.g., 4340 steel) are far below those of superhard materials such as cubic boron-nitride (cBN) and diamonds.

Materials Properties Characteristics			
Materials Properties	Yield Strength (σ_y GPa)	Hardness (H_v GPa)	Fracture Toughness (K_c MPa·m ^{1/2})
4340 Steel	1.5	5.5	50.0
DU	1.0	2.0	35.0
cBN	12.0	48.0	5.0
Diamond	50.0	80.0	8.0

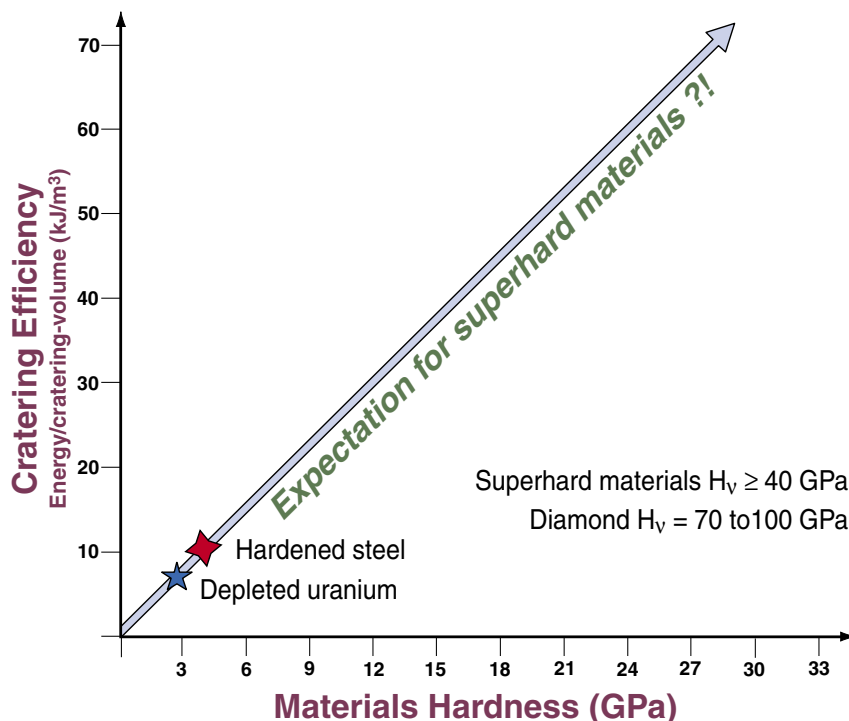
Metal alloys tend to penetrate better than superhard ceramics at relatively low-speed impacts, when brittle fracture and blast shattering are dominant phenomena ($K_c = 35$ and 50 MPa·m^{1/2} compared with 5 and 8 MPa·m^{1/2}). Plastic deformation and blunting/bending of the metal alloys are major concerns in hypersonic, high-speed penetrations.

In contrast, brittle fragmentation in the superhard ceramics may be suppressed as the shock-wave front travels faster than the velocity of crack propagation. Furthermore, high P-T is an unavoidable reality during high-speed impact cratering. High-T weakening is much more severe in metal alloys than in superhard ceramics, and high-P strengthening in metals has much less effect than in ceramics.

Nanocrystalline Materials Synthesis

Research on superhard materials is built on our successful synthesis of nanostructured polycrystalline boron-carbon-nitrides (BC₂N and BC₄N) in

- the starting materials of micro- and nanosize hybrid diamonds and amorphous silicon,
- diamond/cBN and diamond/SiC composites



Cratering efficiency compared with materials hardness. DU and hardened alloy steels have lower material properties than superhard materials such as cBN and diamonds. At relatively low-speed impacts, metal alloys penetrate better than superhard ceramics.

A metal alloy tip blunts, erodes, and bends plastically in hypersonic (\geq Mach 5) penetrations, whereas brittle fragmentation in superhard ceramics may be suppressed as the shock-wave front advances faster than crack propagation.

under high P-T (≤ 20 GPa and ≤ 2200 K) conditions with an amorphous precursor of graphite/hexagonal BN mixtures, and

- large pieces (“bulks”) of superhard B-C-N composites.

A high-energy ball-milling process generates extreme homogeneity as it crushes the starting materials into amorphous phases. This ball-milling process in turn facilitates the nanostructures of high P-T synthesis products. Our indentation tests demonstrated that these nanostructured B-C-N superhard bulks and diamond nanocomposites prevent crack initiation and propagation at polycrystalline grain boundaries. Therefore, we expect those nanocomposites to maintain the integrity of the superhard core upon dynamic impact.

Once optimized, our synthesized products should grow to the size currently available for sintered industrial diamonds (in the 1-inch range). Specific shaping and packing design strategies for the penetrator are closely integrated with the development,

dynamic impact testing, and engineering fabrication of superhard materials.

**Nanostructured superhard materials
provide good penetrator
material for application in robust
deep-earth penetration.**

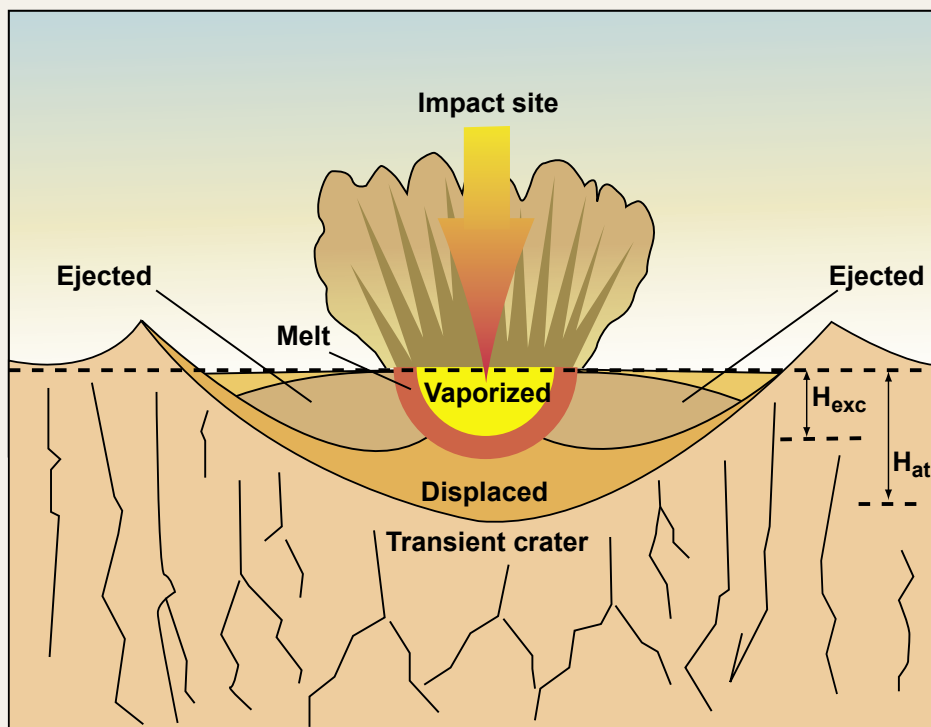
Other potential controlling factors for nanoparticle/amorphous sintering reactions may be the amorphous-grain boundaries of the nanostructured composites that inhibit grain growth during high P-T synthesis. Looking at the nanoscopic details of the amorphous/nanocrystal boundaries, we can compare the composite material with that produced through a conventional devitrification process. The amorphous-crystalline boundary may be significantly better than the macroscopic crystal-crystal boundary. Indeed, the amorphous matrix has the ability to

- relax mismatches from adjacent unit cells that correspond to different phases;

The size and shape of a warhead crater correlate strongly with the materials impedance properties of both penetrator and target. This diagram shows similar impedance properties in both impactor and target-limit penetration, much like a high-velocity meteorite striking the rocky earth.

A “soft” impactor penetrates less efficiently than a “hard” impactor, as when a mud ball hits a brick wall. A hard penetrator bores into its target much more efficiently, creating a deep hole rather than a large crater blast.

Our research on superhard penetrator materials enhances understanding, at nanoscale, of penetrator-material response to dynamic impact.



- absorb vacancies, dislocations, and impurities at the grain boundaries; and
- diminish surface energy and reduce residual stresses in the nanocrystalline grains, substantially improving stability and mechanical performance of the nanostructured bulk materials.

This advanced synthesis technique requires the reduction of oxygen (O) fugacity and specialized techniques such as capsules, buffers, and additives.

Currently, with the development of plasma-arc and/or vapor-grown synthesizing techniques, we expect centimeter-long carbon nanotubes/nanofibers reinforced with an amorphous matrix to greatly enhance hardness, toughness, strength, and corrosion/oxidation resistance. Synthesizing ceramic composites reinforced with nanotubes/nanofibers requires a purification process that removes amorphous carbon particles.

We are working to synthesize nanotube-reinforced composites with an amorphous matrix—a totally different approach from polymer composite synthesis. Our study is directly related to a change of the apparent “wetting-angle” of nanotubes at high P-T.

We also are working to develop a “hairy” nanotube—a nanotube that has many tiny branches growing on its walls—that will reinforce the nanotube by physically and chemically bonding it with the matrix. Our research includes exploring how nanotubes bond strongly to metallic melts and to the amorphous matrix.

Future Studies


Computational modeling and simulation of a material’s mechanical properties will help greatly in designing novel superhard and ultratough nanocomposites. Better understanding of experimental data offers direct insight into material synthesis and penetrator applications. The effects of dynamic P-T on equation of state, yield strength, fracture toughness, and the hardness of polycrystalline diamond, diamond/SiC composite, and B-C-N-O superhard materials will provide experimental data for theoretical and computational modeling.

We model and/or closely measure elastic constants to compare changes in hardness during transition from the amorphous to the crystalline phase at dynamic target impact.

**We are working to synthesize
nanotube-reinforced composites
with an amorphous matrix.**

The hardness of crystalline materials is better defined through deformation and fracture theory, which measures how readily a large number of dislocations and microcracks are generated, move, and coalesce throughout the solid material in response to shear stresses produced by static indentation and/or dynamic impact.

We successfully modeled the physical mechanisms of hardness and toughness in brittle ceramic materials and their relationship to crystal structure and bonding energies, and we plan to investigate the overall performance of superhard penetrators through continuum mechanics.

Our computational studies will provide crucial information that will guide experimental refinements of materials, help in the search for new materials with enhanced properties, and increase understanding of a material’s response to dynamic impact in connection with yield strength, fracture toughness, superhardness, and microstructure of the overall composite materials. 

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Polymeric Foam Characterization: Mechanical Testing

Samples shown actual size.

The nuclear weapons in the stockpile incorporate silicone foam rubber as a critical weapon component. Until 1995, the Dow-Corning Corporation produced the S5370 foam used in weapons, but when production ceased at that time, a replacement foam was needed.

Researchers in the ESA-WMM materials team were tasked with developing a replacement that is as similar as possible to the original S5370 foam. Working with researchers at the NNSA Honeywell Kansas City Plant, the team successfully developed a suitable replacement foam called LK3626.

(See “Developing Replacement Hydrogen-Blown, Silicone Foam Materials,” *Nuclear Weapons Journal*, November/December 2003, pp. 7–9.) This article describes mechanical testing procedures and results involved in selecting LK3626 as a replacement for S5370 foam.

The team investigated a number of replacement foam formulations. Differences between the load-deflection properties of replacement foam candidates and those of S5370 foam—while both types of material are in uniaxial compression—were vital to optimizing the formulations. After tests

showed that several formulations exhibited loads that were, unfortunately, not similar to S5370, the team selected LK3626 as the optimal formulation.

Developing suitable replacement materials such as foams in weapon system lifetime extension

programs (LEPs) is a complex process that must take into consideration the many facets of material properties, especially chemical, thermal, and mechanical properties. Quasi-static mechanical testing of materials under controlled conditions allows researchers to compare and contrast a variety of the mechanical properties

of similar materials. To examine their mechanical properties, the team conducted extensive load-deflection characterization tests over a period of several years on the S5370 and the new LK3626 foams.

To establish a baseline, our researchers first tested specimens of S5370 in uniaxial compression. Then they compared procedural, environmental, and calibration legacy data to discern differences caused by testing and variations resulting from inherent material differences or the effects of aging. Our current testing facilities and equipment allow for faster



Sample disks of LK3626 polymeric foam. We tested several hundred samples of LK3626 in our search for a “like” replacement for S5370 foam for use in nuclear weapons.

sample lot testing and also provide higher fidelity data. The expansive data sets available now enable researchers and engineers to not only quantify but also narrow the uncertainty of the material response.

Researchers on the materials team recently completed development of a “like” replacement for S5370 silicone foam used in nuclear weapons.

To ensure that testing procedures and conditions were identical, we gave special consideration to the S5370 replacement project. Dedicated instrumentation, dedicated fixtures, and custom analysis software gave researchers the best possible data. As best-in-class equipment evolved, it was important to ensure that the recent data could be properly and accurately compared to initial replacement testing data. Sensors and fixturing remained constant, procedures remained mostly constant, and universal testing machine hardware and control systems were upgraded to provide the facility more flexibility with

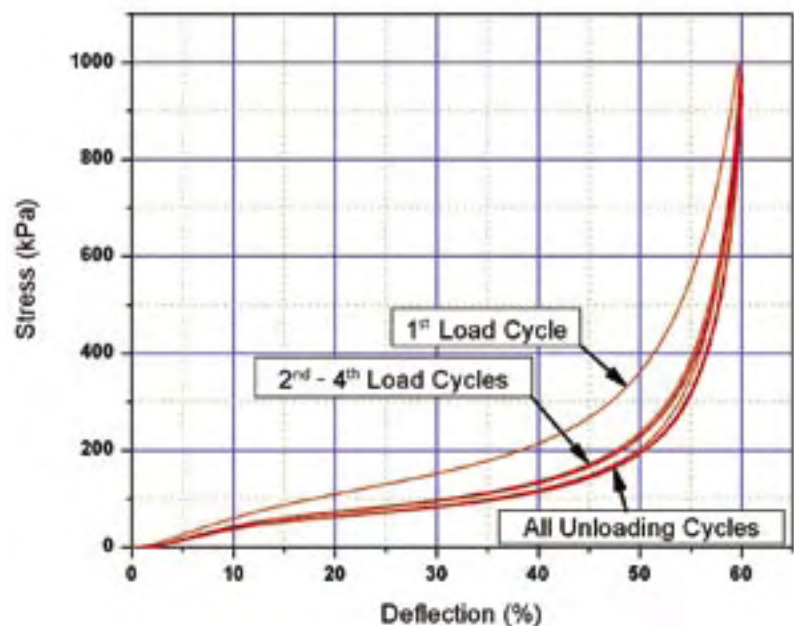
all the testing programs. Calibration procedures and equipment evaluation provide the confidence that recent tests can be correctly compared to older tests conducted in the Weapon Component Test Facility. In addition, we revised analysis software to allow more flexible use and interpretation of the data.

We tested several hundred specimens of LK3626 in a multicycle sequence of loading and unloading. In typical tests, specimens are thin round disks of foam with a nominal thickness of 1 millimeter (mm), an area of 1338.0 mm², and a range of densities from 0.38 to 0.49 grams per cubic centimeter (g/cm³). Each specimen is loaded and unloaded in the test sequence four times. Load values at 10%, 20%, 30%, 40%, and 50% deflection are collected from each cycle for further analysis. So far, only the 20% to 40% fourth-cycle data are of critical interest to the ESA-WMM researchers.

Specimens are loaded and unloaded at the rate of 1.27 mm/minute (0.05 inch/minute). Since each specimen has a slightly different thickness,

Loading and unloading curves for all four cycles of one specimen of LK3626. The loading portion of the first cycle clearly exhibits a higher stiffness throughout most of the deflection range. As noted, all of the unloading portions for each cycle follow the same curve, and the loading portions of cycles 2 to 4 follow the same curve. The loading and unloading curves do not match because of hysteresis typical in visco-elastic materials. (Hysteresis, present in the elastic behavior of materials, is a lag that occurs between the application and removal of a force and its subsequent effect.)

The loading curves of cycles 2 to 4 do not match that of cycle 1 because of the Mullins, or stress-softening, effect. For example, prestretching a balloon before inflating it softens the rubber, requiring less effort to inflate the balloon. When a sample of silicone foam is subjected to load-unload-reload cycles, the accompanying stress lessens because of stress softening, stabilizing after just a few cycles. The stress softening is complete by the end of cycle 3; therefore, data from cycle 4 are compared to determine how good the match is between S5370 and LK2636 formulations of similar specimen densities.



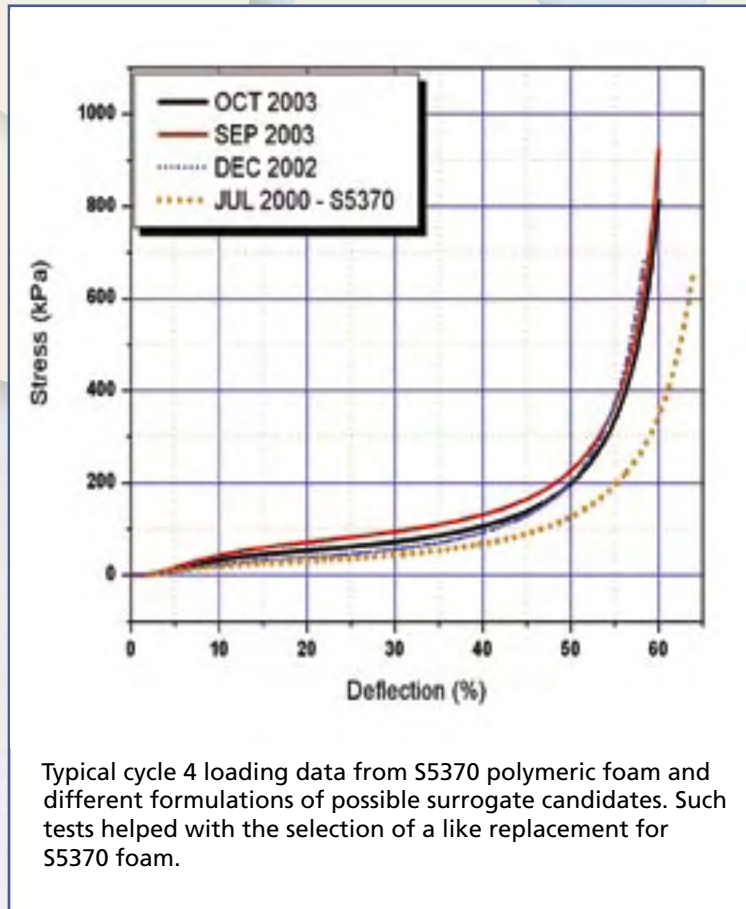
a contact load of 0.1 pound is used to determine the initial thickness of the specimen in the test fixture. This thickness varied slightly from the thickness provided by the ESA-WMM researchers but was found to be within 0.01 mm of that value for each specimen.

Neither the compression platens nor the specimen surfaces were lubricated. Friction reduction for this mode of testing to reduce possible shear stresses in the specimen is not as important in determining the material response for thin foam materials. We minimized surface contamination such as that from dust, chemicals, or human skin cells and oils with the use of nitrile gloves and reclosable plastic bags. We cleaned platens with acetone and inspected them to ensure that they were free of dust or broken particles from previous specimens.

Formulation development, material availability, and testing-support schedules are all factors in the process of evaluating surrogate materials. It is important to have consistent test procedures, test hardware, and analysis to ensure that the material properties are the only things that change, allowing for proper comparison between materials.

We tested large samplings of material in July 2000, December 2002, September 2003, October 2003, and May 2004. We collected data from December 2002 and July 2000 using the same test frames but

different control software. We wrote a new machine control profile in December 2002 that used slightly different “zero” definitions; we used those same definitions in 2003 but on different test hardware and with different machine control software.



In July 2000 all “zero” points for the machine control were set at the specimen thickness provided by the ESA-WMM team. For all later tests, a specimen contact load method determined the “zero” point. That is, the platens were closed until a load was registered outside the signal noise floor of the load cell. The signal noise level was very low, but even at 5% strain the load applied to the specimen is also very

low. Therefore, the differences in deflection levels (calculated based on “zero” point thickness) are caused by the differences in determining the “zero” point thickness as opposed to differences in material response.

We are confident that our extensive testing on the new LK3626 silicone foam provides pertinent high-fidelity data regarding its mechanical attributes and narrows the uncertainty of the material response to evaluate its effectiveness as a replacement in nuclear weapons for the aging S5370 foam. **NWJ**

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Temperature and Strain-Rate Characterization of Polymers and Polymeric Foams

Polymer degradation over time is an important issue for the nuclear weapons in the US stockpile. These weapons contain many polymers, incorporated indirectly as components of composites and directly as structural materials and as cushions between components. Mechanical characterization of these polymers is required for both enhanced surveillance and life extension programs at Los Alamos.

Polymer degradation over time is an important issue for the nuclear weapons in the nation's stockpile.

Researchers in the MST-8 dynamic materials team are responsible for characterizing polymers to determine baseline and aged polymer properties. For example, important polymers that must be fully characterized are S5370 (a silicone foam rubber no longer manufactured by the Dow-Corning Corporation) and LK3626 (its replacement developed by researchers at Los Alamos and the NNSA Honeywell Kansas City Plant); the structural polymer ethylene-vinyl acetate (EVA, but called VCE at Los Alamos); and nitroplasticized estane (NPE), the binder used in the high explosive PBX 9501.

Testing the polymers at both low and high strain rates is important. The team measures the compressive stress-strain properties of these materials using a servo-hydraulic load frame for low-strain-rate testing [0.001 per second (s^{-1}) to $1 s^{-1}$] and a Split-Hopkinson Pressure Bar (SHPB) for high-strain-rate testing ($\sim 2000 s^{-1}$). Load frames are rigid metal frames designed to apply tensile and compressive forces to measure material properties such as strength, stiffness, and toughness. The SHPB transmits well-



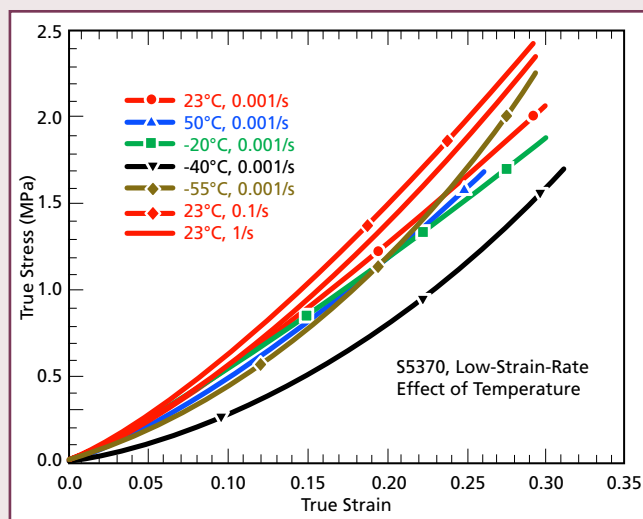
Split-Hopkinson Pressure Bar used for testing polymers and high explosives. The apparatus measures high strain rates by transmitting well-defined compressive waves to samples.

defined compression waves to samples to measure high strain rates.

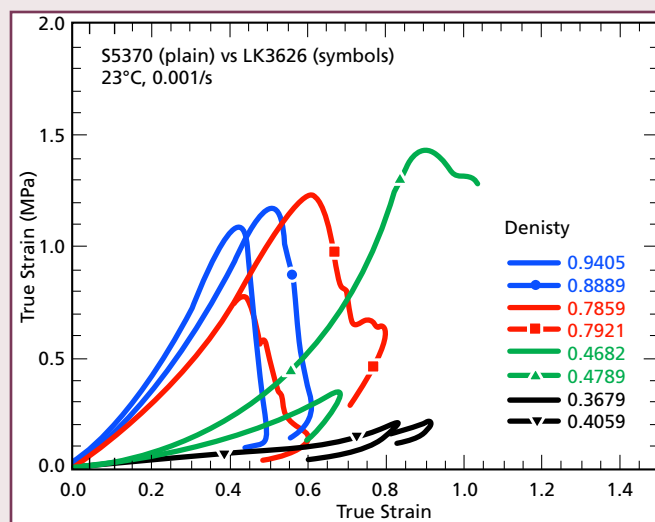
The team uses low-strain-rate characterization of materials for lot-to-lot comparisons between original and replacement materials (the foams) and for general or manufacturing benchmark testing. Researchers must test over a wide range of temperatures and strain rates to determine the mechanical

glass transition temperature (T_g) and to help develop new physically based constitutive models that are used to predict deformation in polymers. The glass transition temperature is the temperature below which a polymer is hard and brittle, like glass, and can fracture (as can a plastic bucket left outdoors on a cold winter day).

We fabricated experimental samples of the polymers and then tested them in uniaxial compression. We



Stress-strain curves for high-density (1.06 g/cm³) S5370 foam as a function of temperature and strain rate.



Stress-strain curves for high-density (1.06 g/cm³) S5370 foam as a function of temperature and strain rate. This figure shows the relative insensitivity of this material to strain rate and temperature for the ranges shown. Most materials would become stiffer with increasing strain rate or decreasing temperature, as shown in the figures on the opposite page.

calibrate the instrumentation annually and test multiple samples for repeatability. These materials are being characterized over the range of temperatures from -55°C to 70°C and from strain rates of 0.001 s^{-1} to $\sim 2000\text{ s}^{-1}$.

We also characterized the S5370 and LK3626 foam materials as a function of density from 0.38 grams per cubic centimeter (g/cm^3) to $1.06\text{ g}/\text{cm}^3$. The average height of the samples is ~ 2 millimeters (mm), and the loading area tested is ~ 20 to 25 mm^2 . We use petroleum jelly as a lubricant for tests conducted on the foam materials above 0°C and no lubrication at lower temperatures. Moly-disulfide grease is used as a lubricant on the VCE and NPE materials for all temperatures.

We tested materials to large strains for all densities and observed an interesting characteristic. For high-density materials (above $\sim 70\%$ theoretical maximum density), the samples fractured at $\sim 50\%$ strain regardless of temperature. Intermediate-density materials fractured at higher strains ($\sim 80\%$), and low-density materials did not fracture at strains less than 100% . The VCE material was deformed to 30% strain; the mechanical glass transition temperature at 0.001 s^{-1} was found to be -30°C , and it shifted to -10°C at 2000 s^{-1} . For higher temperatures (above 23°C) VCE showed little temperature or strain-rate sensitivity. The mechanical T_g of NPE shifted from -40°C to -15°C over the same change in strain rate.

Testing revealed several noteworthy material behaviors.


- The foam stress-strain response was linear before fracture with no observed yield-strength behavior. This response is similar to that seen in brittle materials, although fracture does occur at very high strains.
- The VCE and NPE show two distinct deformation behaviors: viscoelastic behavior at temperatures above T_g and elastic-viscoplastic behavior below T_g . We conducted experiments to determine T_g as a function of strain rate by changing the temperature under constant strain-rate conditions. At low strain rates, a load drop shortly

after the first yield point is commonly observed between 5% and 10% strain. Assuming that both materials were evaluated at approximately 10°C below the glass transition temperature, the VCE showed a higher stiffness than did the NPE.

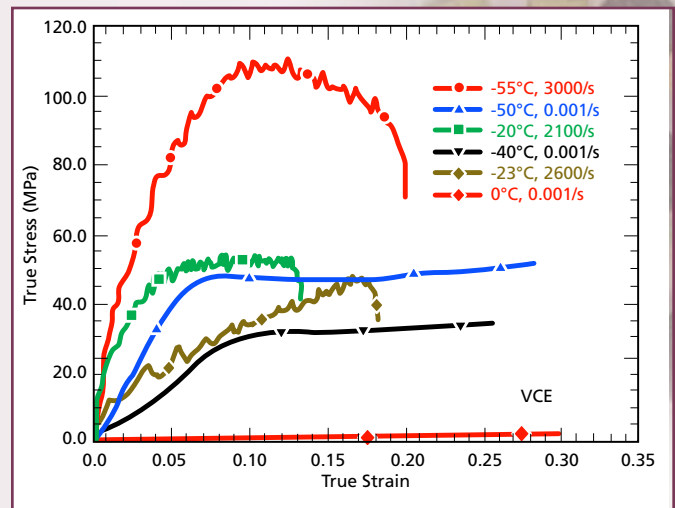
- Tests conducted on VCE and NPE below T_g show little or no dimensional recovery in the specimens until they warm to temperatures above T_g . Although this is not true plastic deformation, the lack of recovery at low temperatures indicates that relaxation in the matrix after deformation occurs at a very slow rate.

We can draw the following comparisons between NPE and VCE.

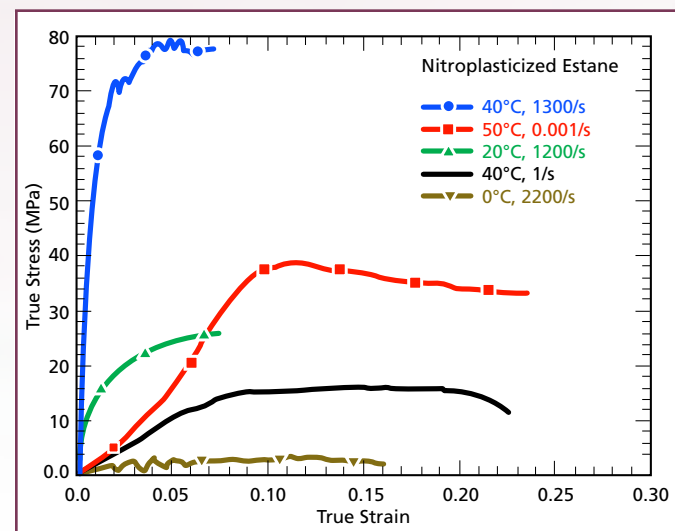
- The compressive stress-strain response of VCE is more strongly dependent on both strain rate and temperature than that of NPE.
- Decreasing the temperature at high strain rate increased the maximum flow strengths, the apparent loading modulus, and the strain-at-maximum-stress for both polymers.
- Measurement of the material properties will be used to develop predictive composite constitutive behavior and failure models.

For all the polymers tested at temperatures above the glass transition temperature, the viscoelastic nature of the samples plays a key role in the apparent loading modulus and the strength. As the temperature decreases, both the apparent loading modulus and strength increase, but the samples recover their original dimensions upon unloading. The unloading curve exhibits some hysteresis but unloads to near zero load for all temperatures and strain rates as long as the samples do not fracture. The drop in flow stress for tests conducted below T_g indicates damage accumulation that is similar to microcracking in ceramic and ceramic composite materials. Further investigation of the damage may reveal whether the damage mechanism is chain scission, crazing, microcrack formation, or something else. 

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Effect of temperature and strain rate for ethylene-vinyl acetate. As mentioned in the description of S5370 deformation, most materials show a pronounced temperature and strain-rate sensitivity. As a point of reference for the strength of these materials, a piece of Gummy Bear candy has more strength at room temperature than any of these materials.



Effect of temperature and strain rate for nitroplasticized estane. Both VEC and NPE show large amounts of strengthening caused by reduced temperature and increased strain rate.

Asymmetry and Mix in ICF Experiments

Inertial confinement fusion (ICF) experiments study the issues surrounding nuclear burn by imploding tiny capsules filled with deuterium-tritium fuel. We have performed experiments that intentionally imposed a low-order asymmetry on the laser illumination that drives the implosion. These asymmetric implosions afford a unique opportunity to study the mechanisms of mix.

Mixing target shell material (in this case, glass) into the fuel of an ICF target diminishes yield through dilution of the fuel and radiative cooling by the higher-Z (heavier) elements. This mix has a major effect on fusion yield; and, while mix probably will never be eliminated, understanding mix is essential to the eventual achievement of fusion energy.

We designed these asymmetric implosion experiments to validate or reject the various mix models integrated into radiation/hydrodynamics codes used to predict the outcomes of ICF experiments. Asymmetry is expected to affect mix through the influence of two factors. Both factors can be understood in a rudimentary form by considering the simplest mix model: the diffusion/convection equation

$$\frac{\partial n}{\partial t} = D \nabla^2 n - \nabla \cdot (\bar{v} n) \quad .$$

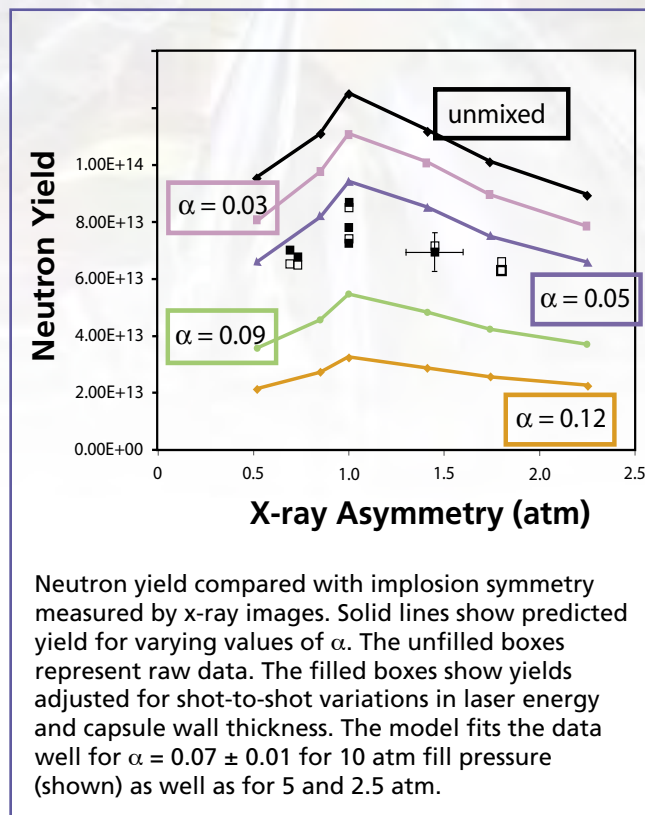
The ∇^2 term on the right side of the equation is sensitive to the curvature of the interface and would be expected to give different results for symmetric, prolate (sausage-shaped), or oblate (pancake-shaped)

implosions. We expect the three different cases to have different contributions from the second term on the right side of the equation as well, as a result of shear flows that develop under the asymmetric drive.

The more sophisticated mix models used in ICF simulations retain the same basic features. Mix is sensitive both to the curvature of the interface, which determines when the “fingers” of shell material caused by instabilities begin running into each other, and to shear flows, which not only carry material from

one place to another but also drive turbulence. The relative contributions from these two factors (curvature and shear) and how they interact or superimpose depends on the specific mix model.

We conducted our experiments at the OMEGA laser facility at the University of Rochester’s Laboratory for Laser Energetics, focusing 23 kilojoules (kJ) (about 22 British thermal units) of 351-nanometer (nm, or billionths of a meter) laser light on the targets in 1-nanosecond (ns, or billionths of a second) square pulses. The targets were glass capsules that



had 1100- μm (millionths of a meter)-diameter and 4- μm -thick walls and were filled with a 50/50 mix of deuterium and tritium at 2.5, 5, or 10 atmospheres (atm) pressure. We individually adjusted the energies of the 60 beams to produce a zero or $\pm 15\%$ component of the second-order Legendre polynomial in the laser drive. The resultant implosions reached ion temperatures of 8 to 12 kiloelectron volts (keV) (around 200 million degrees F) and fusion yields of 1 to 8×10^{13} neutrons.

These experiments provide a stiff constraint on modeling ICF implosions.

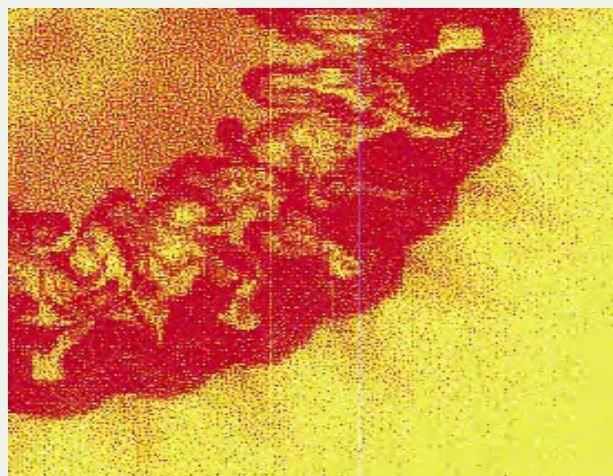
In addition to yield and temperature measurements, we obtained simultaneous x-ray and neutron images. We analyzed the neutron data mathematically to remove the effects of the pinhole point-spread function. The x-rays give information about the higher-Z elements in the shell, while the neutron images reveal the burning core.

We predicted results using the Scannapieco and Cheng mix model, which is a multifluid interpenetration model with one adjustable parameter, α . The model uses the relative velocity of shell and fuel species calculated independently for each zone to obtain corresponding collision frequencies, which then enter the problem as diffusion. Thus, we expect this model to be sensitive to shear flow and to the curvature of the interface. However, in this regime, the model predicts that mix is independent of asymmetry.

We plotted fusion yield against asymmetry of the x-ray images at 10 atm. We did unmixed calculations, in addition to mixed calculations with $\alpha = 0.03, 0.05, 0.09$, and 0.12 . A value for α of 0.07 ± 0.01 fit the data well for oblate, symmetric, and prolate implosions at all three fill pressures. This agreement is a major success of the model.

Even with no mix, yield diminishes with asymmetry because an asymmetric implosion does not produce compression efficiently. The effect of mix is seen by the ratio of yield for the mixed calculation to the yield of the clean calculation. This ratio is approximately constant for a given α , regardless of

asymmetry. (The mixed calculation is nearly equal to the clean calculation times the same constant for the symmetric, prolate, and oblate cases.) Thus the Scannapieco and Cheng model predicts little effect of asymmetry on mix for these experiments. (This prediction might not be true of the model for other regimes.)



The curvature of the fuel-shell interface determines when the "fingers" of shell material, which are caused by instabilities, begin running into each other. Note: This figure illustrates the effect of curvature but is not intended to portray these particular implosions.



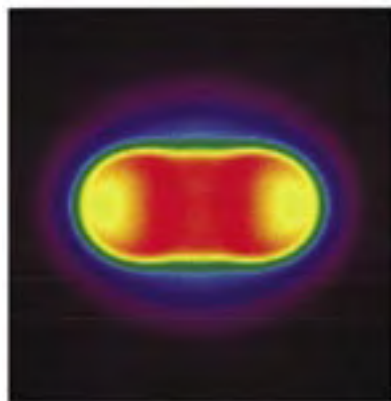
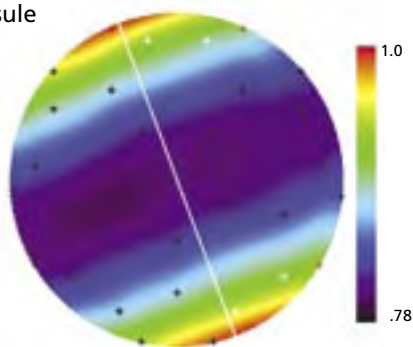
The OMEGA laser at the University of Rochester's Laboratory for Laser Energetics focuses 60 beams of laser energy onto a target (23 kJ in 1 ns). This inside view of the vacuum vessel during a shot shows the capsule (small bright reddish object) and the snouts of various diagnostics (e.g., x-ray and visible cameras).

The effect of asymmetry on mix is seen from the comparison of clean with mixed results, but only the mixed result can be verified experimentally. Another hydrodynamic code, together with another mix model, might provide different results about the effects of asymmetry on mix but still fit the data. Only a hydrodynamic code/mix model combination can evaluate the relationship between asymmetry and mix; the data will substantiate or reject the model.

Apparently, the various asymmetry-related influences that affect yield almost cancel each other in our model, and the data fit the model within the uncertainties. This near-cancellation of various effects is a definite testable outcome and should not be considered a null result. These experiments provide a stiff constraint on modeling ICF implosions. We hope that other investigators will accept the challenge to apply their mix models to this well-diagnosed data set. [NWJ](#)

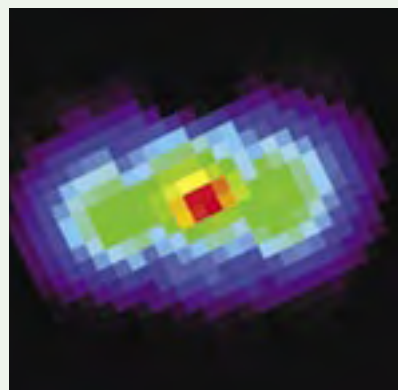
Cindy Christensen, 665-6576, cchristensen@lanl.gov

Laser illumination on the surface of the capsule for an oblate implosion. The laser drive is stronger along the axis (red) and weaker around the equator (black or dark purple). The symmetry axis is shown in white. White crosses show the centers of the beams.

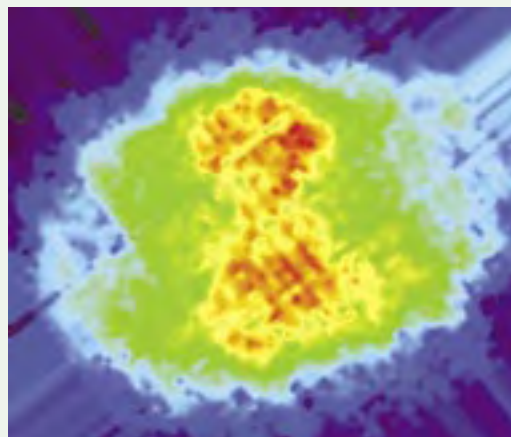
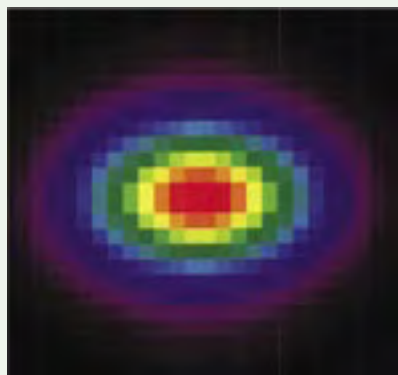


Predicted x-ray image for $\alpha = 0.07$, showing good qualitative agreement with the data. The stronger drive perpendicular to the axis squeezes the capsule down, giving a narrow, indented waist. Lower-emission material is squeezed out along the axis, producing the observed "bubbles" (232- μ m plot). The emission from the waist produces a bright band in the time-integrated images.

Neutron emission from the capsule during this prolate implosion is imaged using a pinhole. Because of the penetrating ability of high-energy neutrons, the "pinhole" was actually a 10-centimeter-thick block of tungsten with a tapered groove along the axis. Because the effective radius of the aperture is unavoidably greater than the clear opening, we applied mathematical processing to remove the effects of the point-spread function (each pixel = 6.3 μ m; 164- μ m plot).



An x-ray image for the same prolate implosion. We integrated the signal over the time of the implosions; x-rays reveal the higher-Z material of the shell, while neutrons image the burning core (232- μ m plot).



Predicted neutron image for the same prolate implosion with $\alpha = 0.07$ (164- μ m plot).

Pollution Prevention in Weapons Programs

Because nuclear weapons research is the LANL's primary national security mission, it's not surprising that teams and individuals involved in NNSA programs have implemented many of the Laboratory's most successful pollution-prevention projects.

For more than a decade, the Laboratory's Pollution Prevention Program has encouraged process change to reduce programmatic risk; the participation of the nuclear research teams is especially important because NNSA's pollution prevention projects often reduce the generation of low-level (LLW), mixed low-level (MLLW), and transuranic (TRU) wastes—wastes that are expensive and difficult to handle. Consider the following costs:

- disposal of each cubic meter (m^3) of LLW ranges from \$650 to \$2,879;
- disposal of MLLW ranges from \$32 to \$40/kilogram (kg); and
- disposal of TRU waste ranges from \$1,313 to \$2,879/ m^3 .

The employee-based pollution-prevention projects described here show how Laboratory workers are finding innovative ways to improve mission performance, promote good economics and worker safety, and reduce pollution to the workplace and the environment.

NMT and RRES: Reusable Containment Tent

The reusable containment tent developed by a team from NMT Division and the RRES pollution prevention team is an excellent example of a pollution-prevention project that considerably reduces current and future waste volume.

Contamination-containment structures are used primarily to prevent the escape of contamination when



This reusable aluminum-frame containment tent is nonflammable and sturdy, does not leak contamination into the surrounding area, and can be assembled by three people in less than 3 h. It can be decontaminated quickly and stored in a 30-gal. drum.

a glove box in a radiological control area is opened for maintenance. In the past, wood-and-plastic containment structures built around the affected glove box increased the risk of fire and the need for extra safety precautions. Building or disassembling each structure required about 120 person-hours, and the wood and plastic parts were disposed of as LLW. The Laboratory used about 25 of these structures every year; each structure generated approximately 90 cubic feet (ft^3) of LLW. Because there was always a small risk of tearing the walls of the wood-and-plastic tents, workers in the surrounding area wore respirators to perform their normal work when a tent was in use. Sometimes entire rooms shut down while a glove box was being serviced, which substantially slowed mission progress.

The reusable tents have several other advantages over the wood-and-plastic tents that had to be constructed on the site, such as the following.

- *Superior containment.* The reusable tents are constructed of a nonflammable fabric that significantly reduces the risk of fire. Also, because the tents are sealed structures, workers in the room where a tent is located can continue their normal activities.
- *Reduced labor costs.* In less than 3 hours (h), 3 people can set up a reusable tent, which avoids significant labor expenses. Construction consists

of assembling the aluminum frame, connecting the reusable tent to a portable vacuum system, inflating the tent, and attaching the tent to the frame.

- *Less LLW to dispose of.* After workers decontaminate a reusable tent below detection levels—using only wet cheesecloth—the tent can be stored in a 30-gallon (gal.) drum for later use. Because the tent can be reused, the generation of 2,000 cubic feet (ft³) of LLW can be avoided annually.

Decreased construction and disassembly time, combined with the lost work time that can be avoided now by continuing work in rooms where glove boxes are being serviced, will increase productivity and save a significant amount of labor. NMT Division anticipates annual savings of \$2 million in reduced waste-generation and labor costs.

NMT-9: Plutonium-238 Recovery Method

Another example of a successful pollution-prevention project is NMT-9's new method for recovering plutonium-238. NMT-9 recycles fuel that contains plutonium-238, recovering acidic and basic liquids that contain plutonium-238 so that the residual plutonium can be removed and solidified.

In the recovery process, sodium hydroxide or nitric acid solution may be added to the waste to achieve the correct hydrogen ion activity (pH 4). Unfortunately, this practice can more than double the initial volume of liquid. Occasionally, the paper filters used to catch the precipitate failed, and the filtrate required a second treatment. Because both acidic and basic liquids contaminated with plutonium-238 were sent through the recovery process, the team mixed exact quantities of the two streams to produce the correct initial pH. They added a degradation-resistant polypropylene filter to the paper filter, which completely prohibits the passage of plutonium-238.

NMT-9's new recovery process requires about 50% less time, saving approximately 40 h of labor/month. The new process also cuts the production of TRU waste by 50%, or 125 liters/month, and saves about \$150,000 in annual treatment costs.

Plutonium Facility and CMR Building: Nonlead Bricks

A third example of successful pollution prevention is the use of tungsten- or bismuth-based bricks to protect workers from exposure to radiation. Traditional lead bricks used during experiments that involved radiation became MLLW when the bricks were no longer usable; the lead was potentially toxic to workers, and disposal was expensive.

As part of a hazardous-material elimination program, team members from two LANL radiological control groups substituted lead bricks with bismuth- or tungsten-based bricks, depending on shielding requirements. The team now uses tungsten-based bricks when shielding needs relate to density and bismuth-based bricks when shielding needs relate to molecular weight. The tungsten-based bricks shield as effectively as lead bricks; bismuth-based bricks shield more effectively than lead bricks.

Hazardous materials coordinators at the Plutonium Facility and at the Chemistry and Metallurgy Research (CMR) Building plan to remove approximately 2,000 more lead bricks from their facilities by 2006 and replace them with nonhazardous substitutes. In fact, lead will no longer be purchased for any shielding purposes in some areas, thereby eliminating an expensive waste stream (disposal of MLLW costs up to \$40/kg) and a potential toxicity hazard to workers.

Importance of Worker Input

These pollution-prevention projects that originated in three nuclear research groups indicate the importance of worker input to waste reduction at the Laboratory. Pollution prevention projects initiated at the grass-roots level have achieved millions of dollars in cost reductions and have prevented the generation of thousands of kilograms of waste of all kinds. These projects were not required—they were employee efforts to lessen the impact of Laboratory activities on the environment, reduce costs and labor, and help meet Laboratory waste-reduction goals. Their efforts represent the tip of the iceberg in potential pollution-prevention and waste-stream elimination opportunities. **NWJ**

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Protecting Against Terrorism: SECON Access Control Posts

After September 11, 2001, LANL security personnel established additional Security Condition (SECON) access control posts on roads near sensitive Laboratory locations. Guard stations have long existed in many Laboratory areas, but LANL security officers determined that security could be enhanced by limiting access to areas near additional sensitive facilities and operations to holders of LANL- or DOE-issued security badges.

“The events of 9/11 have changed the way we and other nuclear facilities across the nation respond to potential threats,” says Michael Irving, senior security advisor for the Los Alamos Weapons Physics Directorate.

Temporary structures served as the new SECON access control posts until mid-April 2004; now permanent stations are in place. Protective Force Security Police Officers staff some posts 24 hours a day, 7 days a week. If a particular post is not staffed after working hours or on weekends, locked

gates prohibit access to the sensitive area served by that SECON post. Anyone who needs access to an area where a post is closed must enter through an alternate SECON post that is open.

At every SECON level, all motorists, including motorcyclists, must come to a complete stop at an access control post, present appropriate security badges, and wait until guards allow the drivers to proceed. If one person in the vehicle has an acceptable badge, guards permit that vehicle to enter the sensitive location. If no one in the vehicle has a proper badge, guards order the driver to turn around and leave the area.

Appropriate badges include

- all Q- and L-cleared LANL badges;
- DOE standard badges, including badges from other DOE laboratories;


- certain visitor and temporary badges, accompanied by other photo identification; and
- special LANL-organization-requested uncleared badges issued to truck drivers who make regular deliveries to the Laboratory.

At higher SECON levels, pedestrians and bicyclists also must stop at SECON posts and present appropriate security badges. A level change is based on credible specific potential threats to security or Laboratory operations.

If a motorist does not stop at a SECON access control post, security police officers have orders to consider the vehicle a potential security threat. They will pursue the driver, search the vehicle, and take necessary steps to ensure the safety of LANL's property and personnel. If the driver who doesn't stop is a LANL employee, he/she will receive a security infraction.

If a driver is disabled or has vehicle problems inside an area protected by SECON posts, he or she can arrange for help through LANL's Central Alarm Station, 667-4437.

Unbadged drivers of delivery trucks must stop at a designated truck inspection station. If guards examine the vehicle, check all paperwork, and find everything in order, they issue a pass to the driver and allow the truck to proceed. The pass is good for that delivery only. If an unbadged driver makes regular deliveries, the LANL organization that receives the deliveries can get an uncleared badge issued for multiple visits.

"These enhanced security measures are just one aspect of a graded approach that provides layered security protection for our personnel and resources," says Irving. "Our employees are aware, our security personnel are vigilant, LANL leadership is fully engaged, and our protection strategies are sound. We take our security mission very seriously." 

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Acronyms Used in this Issue

C-AAC	Chemistry Division, Actinide Analytical Chemistry Group
DoD	US Department of Defense
DOE	US Department of Energy
DOJ	US Department of Justice
DTRA	US Defense Threat Reduction Agency
ESA	Engineering Sciences and Applications Division
ESA-WMM	ESA-Weapons Materials and Manufacturing Group
ESA-WR	ESA-Weapon Response Group
HSR	Health, Safety, and Radiation Protection Division
HSR-2	Occupational Medicine Group
HSR-5	Institutional Industrial Hygiene and Safety Group
LANL	Los Alamos National Laboratory
LLNL	Lawrence Livermore National Laboratory
MST	Materials Science and Technology Division
MST-8	Structure/Property Relations Group
NMT	Nuclear Materials Technology Division
NMT-9	Plutonium-238 Science and Engineering Group
NNSA	National Nuclear Security Administration
PS	Performance Surety Division
PS-7	Performance Indicators Group
PS-13	Training Services Group
RRES	Risk Reduction and Environmental Stewardship Division
SNL	Sandia National Laboratories
STRATCOM	US Strategic Command
UC	University of California

Management Safety Walk-Arounds: Interacting with Workers

Ensuring that work is performed safely is a line manager's number one priority. Keeping work safe involves setting performance objectives, observing behavior, identifying opportunities to improve, providing feedback, and enforcing established performance expectations.

Line managers who use their walk-around time effectively can create a culture of safety in their areas of responsibility. Line managers who make themselves accessible to their workers during a walk-around demonstrate that safety is important to them and that they are interested in making the work and the workplace safer and more efficient.

No-Fault Discussion

A safety walk-around should be a cooperative exchange between managers and workers. A walk-around is of value only when open, frank discussion occurs between managers and workers about

- the work process,
- its hazards and controls, and
- problems and difficulties that need correction.

This interaction between line managers and workers should result in a performance-based evaluation of work. This exchange in turn ensures that work is conducted in a safe, productive, and cost-effective manner.

How do you, as a line manager, establish a no-fault discussion with workers?

As you enter the work area to conduct your walk-around, take a few seconds to observe what the workers are doing. Introduce yourself, if necessary, and explain why you are there. Your words and actions should make it clear that you are conducting a walk-around—not an audit. Ask the workers if they have any safety concerns about what they are doing or about the operations and the work area. You could start with the following questions.

Walk-Around Checklist

Is your walk-around

- ✓ *based on interaction with workers?*
- ✓ *performed with safety expectations?*
- ✓ *focused on worker behavior—not just inspection items?*
- ✓ *aimed at workplace hazards?*

- What hazards have you identified in your operation or work area?

- What has been or needs to be done to mitigate those hazards?
- How can we make this operation safer and/or more efficient?
- As your manager, what can I do to ensure that your work environment is safe?

Two-Way Communication

The key element in the walk-around process is interaction—two-way communication—between the line manager and the people doing work. The workers know and understand the job, including problems and areas that need improvement; managers must solicit workers' observations, concerns, and suggestions and follow through on all agreements reached during a walk-around. To facilitate a comfortable exchange, ask the following questions about the conduct of operations, compliance with procedures, and any other issues relevant to safety and/or efficiency.

- Are you using a current, approved procedure or integrated work document (IWD)? How do you know?
- Do you follow the procedure or IWD steps exactly and in sequence? What do you do if a procedural step is not practical in a specific work situation? What is required to change the procedure or IWD?
- What happens if a step is missed or completed out-of-order? Do you think that matters?
- Have you observed indications of unapproved shortcuts or changes to the procedure or IWD? What do you do then?

**The key element is interaction
between the line manager and the
people doing work.**

If workers are taking shortcuts or if you see evidence of unapproved procedural aids (such as notes taped to equipment), discuss these things with the appropriate workers at the end of the walk-around—unless you perceive an immediate safety hazard. The use of unapproved procedural aids may indicate that the procedure or IWD needs to be modified or that additional operator training is needed.

Ergonomic Issues

Ergonomic risk factors can be present in computer and noncomputer work areas. Observe workers at their workstations and ask them to demonstrate how they perform specific operations or activities.

In noncomputer areas, look for excessive reaching, twisting while lifting, gripping or holding objects for long periods, and pushing or pulling heavy loads. In computer areas, look at posture (slouching, leaning, tilted neck and wrists), monitor height, keyboard surface, and mouse location. For ergonomic issues, ask questions such as these.

- What ergonomic risk factors are associated with your work? What has been done to mitigate those risk factors?


- How many hours per day do you spend on your computer or at your workstation? How often do you take a break? Do you ever work longer than an hour without switching tasks or taking a break?
- If you develop discomfort (e.g., tingling, numbness, or pain) related to work you perform, whom should you contact?

Managers must be sure that workers are aware that awkward posture, excessive force, and repetitive motion are ergonomic risk factors and that institutional resources are available to help prevent unsafe work situations before an injury occurs. These resources include PS-13 ergonomics training, the ergonomics Web site (<http://int.lanl.gov/safety/ergonomics/ergonomics.shtml>), the ergonomics demonstration room (665-3190), and the HSR-5 ergonomist (665-3642). Managers should encourage workers to report ergonomic discomfort to their supervisors and HSR-2 and schedule ergonomic evaluation by calling 665-6605. Early intervention is key to decreasing the severity of ergonomic injury.

Physical deficiencies identified in walk-arounds must be corrected, but they should not be the focus of a walk-around. Because compliance inspections focus on objects—e.g., equipment, machinery, tools—these inspections are less effective in evaluating worker safety than performance-based walk-arounds, which focus on worker behavior—i.e., work that is being performed.

In summary, to ensure effective performance-based walk-arounds and walk-around findings that improve the safety and efficiency of operations,

- observe work (or a demonstration/mockup of the work to be conducted) and
- engage in meaningful dialogue with workers about their operations and work environment.

For further information on the management safety walk-around program, contact Roger Kruse, PS-7, at 665-8331. 

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Point of View, continued from page 1

for nuclear safety noncompliance requirements. If the work being performed has anything to do with handling, monitoring, retrieving, treating, sampling, analyzing, or evaluating risks associated with or using radioactive materials, PAAA applies.

Each Laboratory division identifies a facility PAAA point of contact (POC) to work with division subject-matter experts in quality, radiation protection, and safety basis to identify, report, and correct nuclear safety noncompliances. POCs evaluate contractor assessments and walk-arounds, identify potential nuclear safety issues, and review actual and perceived noncompliances.

Division managers are trained to recognize and ensure documentation of nuclear safety issues. They also can call on the Laboratory PAAA Office for assistance in identifying issues, documenting nuclear safety noncompliance reviews, and reporting noncompliance issues to DOE/NNSA, as appropriate. However, Laboratory managers usually identify safety issues and begin appropriate corrective processes before most PAAA noncompliances are formally identified.

Historically, the weakest link in this process was the Laboratory's failure to review facility-related issues at the institutional level and to ensure appropriate corrective actions. However, a recently amended closure process greatly improved this shortcoming. Now, the PAAA Working Group and facility POCs review and identify facility issues and forward their recommendations for institutional-level corrective action to the Nuclear Safety Executive Board (NSEB) before submitting these recommendations to DOE/NNSA. Since September 2003, 16 nuclear safety noncompliance reports have been closed, some of which date back to 1999, with no recommendations for enforcement actions.

PAAA Enforcement Process

Defined in 10 CFR 820, Procedural Rules for DOE Nuclear Activities, the DOE PAAA enforcement program is the mechanism for action against contractors who permit unsafe actions or conditions that violate nuclear safety requirements. DOE has the authority to issue Notices of Violation (NOVs) when noncompliances—which are recorded

permanently in a noncompliant contractor's DOE file—are identified. Such action reduces the contractor's potential for future DOE projects. The primary consideration in determining whether DOE/NNSA will initiate enforcement action is the safety significance—actual or potential—of a violation, coupled with a determination of how aggressively the contractor identified, reported, and corrected a problem within the affected facility and/or across the institution, as appropriate.

**The primary consideration
in determining enforcement action
is the safety significance of a violation.**

In cases involving for-profit contractors, DOE has the authority to issue fines for violations of nuclear safety rules up to \$110,000/day per occurrence and the DOJ has the authority to issue criminal penalties.

Because LANL is a not-for-profit educational institution, the law exempts the Laboratory from paying civil penalties that could result from enforcement actions. Since 1996, the Laboratory has received six NOVs with civil penalties that would have totaled \$1,542,500 (A preliminary NOV with a waived penalty of \$770,000 is pending against the Laboratory.) The not-for-profit exemption will be removed in the next renewal of the PAAA, expected in 2004, and the Laboratory is subject to other civil enforcement mechanisms.

Most potential violations of PAAA lack the requisite level of safety significance to warrant civil penalties. Less than 5% of the contractor-identified noncompliances resulted in enforcement action; approximately 85% of Laboratory-identified noncompliances were closed with no enforcement action because the Laboratory followed the self-identification process and took corrective action.

This potential for mitigation is the heart of PAAA's three-step enforcement process—these incentives are designed to encourage contractors to create a positive on-the-job safety culture by complying with mandated standards that protect workers and the public. They include options for DOE to take


no enforcement action or to mitigate a civil penalty, if the contractor has established a program to

- self-identify and report problems to DOE,
- conduct in-depth investigations and causal analysis, and
- initiate timely and effective corrective actions.

The Laboratory PAAA Office works closely with DOE in responding to each situation. DOE's innovative approach to enforcement is intended to avoid personnel-intensive inspections and encourage contractor ownership of compliance and safety. This approach has resulted in a more effective and efficient regulatory process that, in conjunction with other elements of the DOE safety management

program, improves public and worker safety at DOE sites such as the Laboratory.

Individual Worker Responsibility

As a best business practice and because managers cannot correct a problem for which they have no information, all Laboratory workers are encouraged to use any available avenue (e.g., phone calls, e-mail messages, in-person discussions, written notes) to inform managers, their facility PAAA POCs, or the Laboratory PAAA Office of a suspected nuclear—or any other safety—noncompliance. Only by our aggressive self-identifying, reporting, and correcting problems will we assure the work force, managers, UC, DOE/NNSA, and the public that we understand our nuclear safety requirements and that we are committed to making the Laboratory a safer place to work. 

Define that, please!

noncompliance—failure to comply with DOE-mandated nuclear safety requirements

Examples of potential noncompliances at the Laboratory are incorrect torque on a waste drum packaged for the Waste Isolation Pilot Plant, radiation contamination of an employee, and use of a draft procedure that did not include quality assurance requirements.

nuclear incident—"...any occurrence, ...damage or injury arising out of or resulting from the... hazardous properties of source, special nuclear material or byproduct material...." (USC, Title 42, Chapter 23, Subchapter 1, Sec 2014, *Definitions*)

Congress's broad definition was designed to protect the public from any form of damage that could arise from the special dangerous properties of materials used in the atomic energy program.

Nuclear Safety Executive Board—Laboratory board that strengthens LANL's nuclear safety posture by elevating the details of issues with nuclear safety implications to the attention of senior executive management

The NSEB ensures that institutional issues and their corrective actions are appropriately identified and closed. Its monthly meetings are chaired by the Laboratory Director and

attended by the Laboratory's associate directors with technical advisors, a UC representative, a board advocate, and subject-matter experts as needed.

positive incentive—system that rewards DOE contractors who establish and follow a proactive process of self-identifying, reporting, and correcting PAAA noncompliance issues before they adversely impact individuals or the facility

public liability—"...any legal liability arising out of or resulting from a nuclear incident or precautionary evacuation...." (USC, Title 42, Chapter 23, Subchapter 1, Sec 2014, *Definitions*)

Although the PAAA does not define legal liability, legislative history clearly indicates that state tort law determines which legal liabilities are covered. A contractor is fully indemnified against public liability even if a noncompliance was caused by acts of gross negligence or willful misconduct.

safety basis—documented safety analysis and hazard controls that provide reasonable assurance that a DOE nuclear facility can be operated safely in a manner that adequately protects workers, the public, and the environment (10 CFR 830.3, *Definitions*)

A BACKWARD GLANCE

Oppenheimer: Unique in the Scientific World

April 22, 2004, marked the 100th anniversary of the birthday of J. Robert Oppenheimer, the first Director of Los Alamos National Laboratory and the man who led a group of blue ribbon scientists to produce the world's first atomic bombs. Los Alamos proudly pays tribute to this remarkable man through the words of people who knew him.

"Oppenheimer's fascinating personality played a major part in his unique powers as a teacher. His course was an inspirational, as well as an educational, achievement. He transmitted to his students a feeling of beauty of the logical structure of physics and an excitement in the development of science."

—*Robert Serber*, Manhattan Project physicist and student of Oppenheimer at the University of California, Berkeley

"A less likely choice on the basis of personality and experience could hardly be imagined.... Yet he constructed that laboratory [Los Alamos] from the ground up and made it into a most effective and deadly instrument for the application of science to destruction. At the same time, he created an atmosphere of excitement, enthusiasm, and high intellectual and moral purpose that still remains with those who participated."

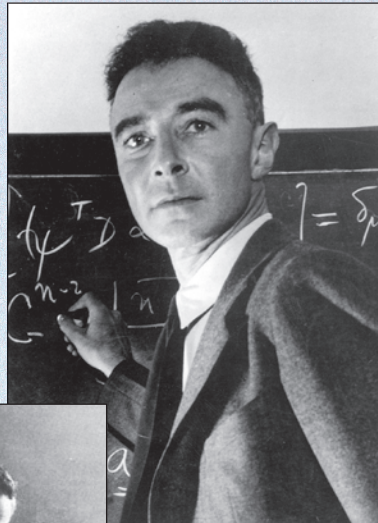
—*I. I. Rabi*, Nobel laureate in physics and consultant to Los Alamos in the 1940s

"It was a marvelous choice. Los Alamos might have succeeded without him, but certainly only with much greater strain, less enthusiasm, and less speed. As it was, it was an unforgettable experience."

—*Hans Bethe*, Nobel laureate in physics and Los Alamos Theoretical Division director in the Oppenheimer years

"He was naïve in politics. If he hadn't been, his career would have been quite different."

—*Dorothy McKibbin*, official receptionist and welcome officer for Los Alamos during the Oppenheimer years



"Any single one of the following contributions would have marked Oppenheimer as a pre-eminent scientist: his own research work in physics; his influence as a teacher; his leadership at Los Alamos; the growth of the Institute of Advanced Study as a leading center of theoretical physics under his directorship; and his efforts to promote a more

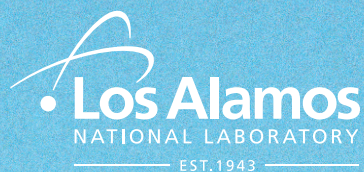
common understanding of science. When all is combined, we honor Oppenheimer as a great leader of science. When all is interwoven with the dramatic events that centered around him, we remember Oppenheimer as one of the most remarkable personalities of this [20th] century."

—*Abraham Pais*, physicist, historian, and colleague of Oppenheimer at Princeton University's Institute for Advanced Study

"Dr. Oppenheimer, ...your contributions to our basic knowledge make your achievements unique in the scientific world."

—*Lyndon B. Johnson*, President of the United States, on awarding the Atomic Energy Commission's Enrico Fermi Award in 1963

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